# Stability and Performance Improvement with Feedback in VRM Transconductance Error Amplifiers

## A Case Study using the Sandler State Space Average VRM Model

**Session Presented By: Benjamin Dannan**

**Date: 5 October 2022**

**Track: Technical Session**



# Presenter Bios

Benjamin Dannan is a Technical Fellow and an experienced signal and power integrity (SI/PI) design engineer, advancing high-performance ASIC and high-speed digital designs. He is a Keysight ADS Certified Expert with expert-level proficiency in high-speed simulation solutions, multiple 3D EM solutions, and multiple test and measurement solutions. Benjamin holds a cybersecurity certification, a BSEE from Purdue University, and a Master of Engineering in Electrical Engineering from The Pennsylvania State University. He has numerous publications and received the prestigious DesignCon best paper award in 2020.

Steve Sandler has been involved with power system engineering for more than 40 years. Steve is the founder and CEO of PICOTEST.com, a company specializing in instruments and accessories for high-performance power systems and distributed system testing. He frequently lectures and leads workshops internationally on the topics of Power Integrity and Distributed Power System Design. He is a Keysight Certified EDA expert.

Heidi Barnes is a Senior Application Engineer for High-Speed Digital applications in the EEsof EDA Group of Keysight Technologies. Her recent activities include the application of electromagnetic, transient, and channel simulators to solve signal and power integrity challenges. Author of over 20 papers on SI and PI and recipient of the DesignCon 2017 Engineer of the Year. Heidi graduated from the California Institute of Technology in 1986 with a bachelor’s degree in electrical engineering. She has been with Keysight EEsof since 2012.

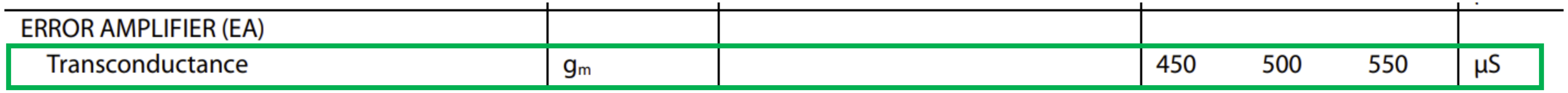
# Overview

- Why do we care about Gm tolerance of the error amp inside VRMs?
- Background on transconductance amplifiers
- Basics of feedback loops and control theory
- Case study – Gain sensitivity and nonlinear distortion
- Case study – VRM output impedance and stability
- Summary & conclusion

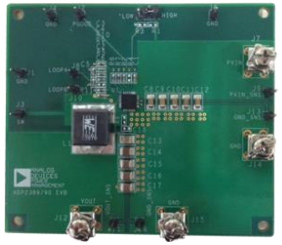
# Why do we care about the Gm tolerance of the Error Amp inside of VRMs?

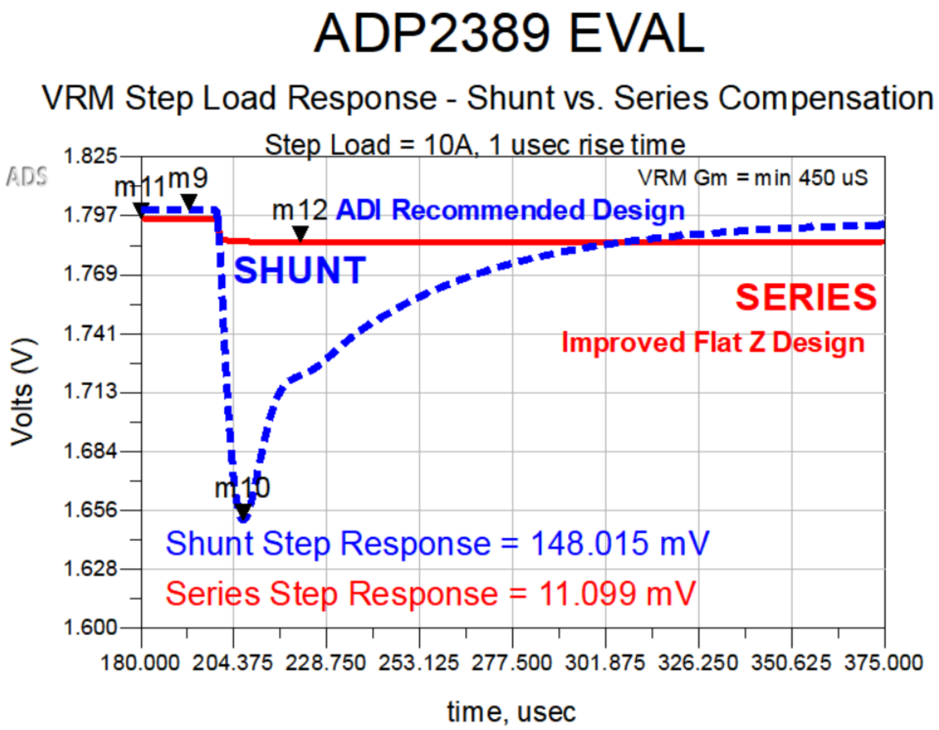
## Transient Response Shunt vs. Series Compensation

**Per ADP2389 Datasheet**

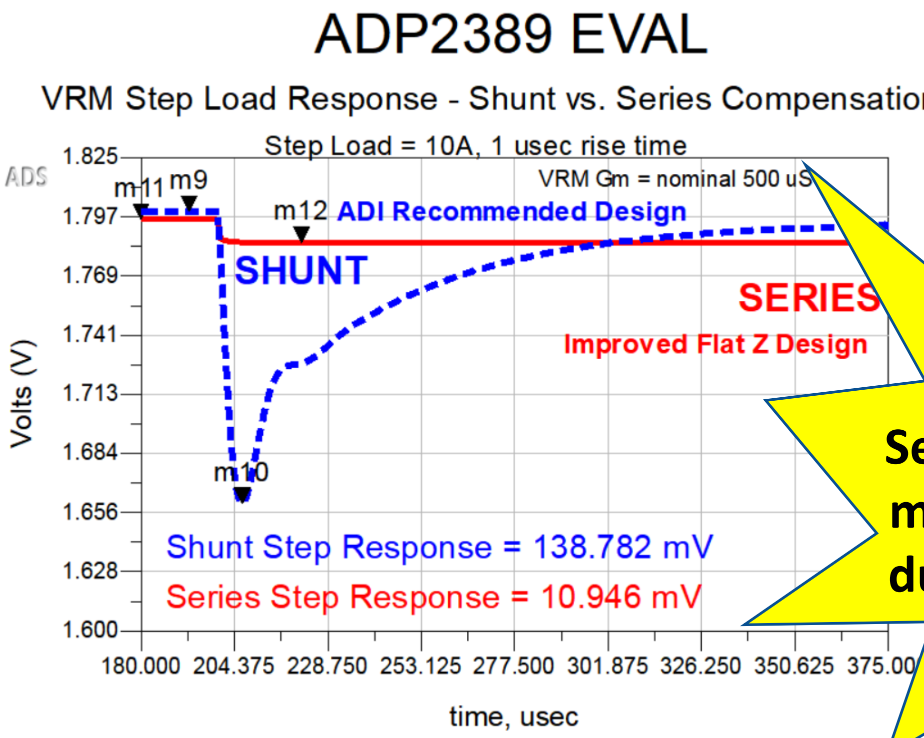


| | | | | | | |
|---|---|---|---|---|---|---|
| ERROR AMPLIFIER (EA) | | | | | | |
| Transconductance | $g_m$ | | 450 | 500 | 550 | µS |





ADP2389 Datasheet ***Gm min = 450 uS***



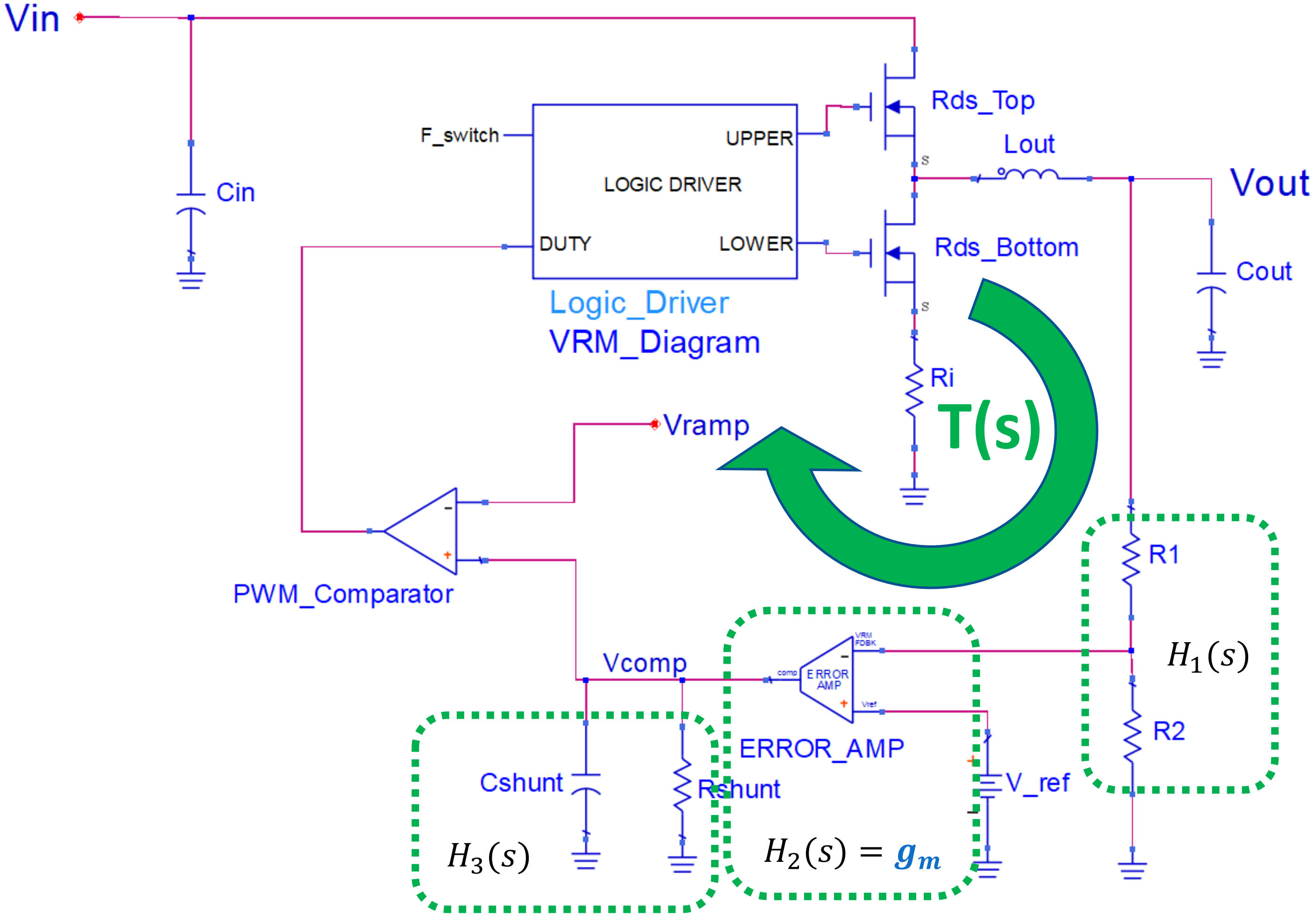
ADP2389 Datasheet ***Gm nominal = 500 uS***

**Series compensation mitigates the effects due to Gm tolerance**

Let's talk about how to improve your design WITHOUT ADDING COST

# The Voltage Regulator Module (VRM)

- What is the buck regulator VRM composed of?
  - Logic Drivers
  - Switches
  - PWM Comparators with Slope Compensation
  - Error Amplifier
- Loop gain T(s) is part of the VRM's closed-loop transfer function
  - The Error Amplifier feedback loop and **transconductance** affect the VRM's output impedance



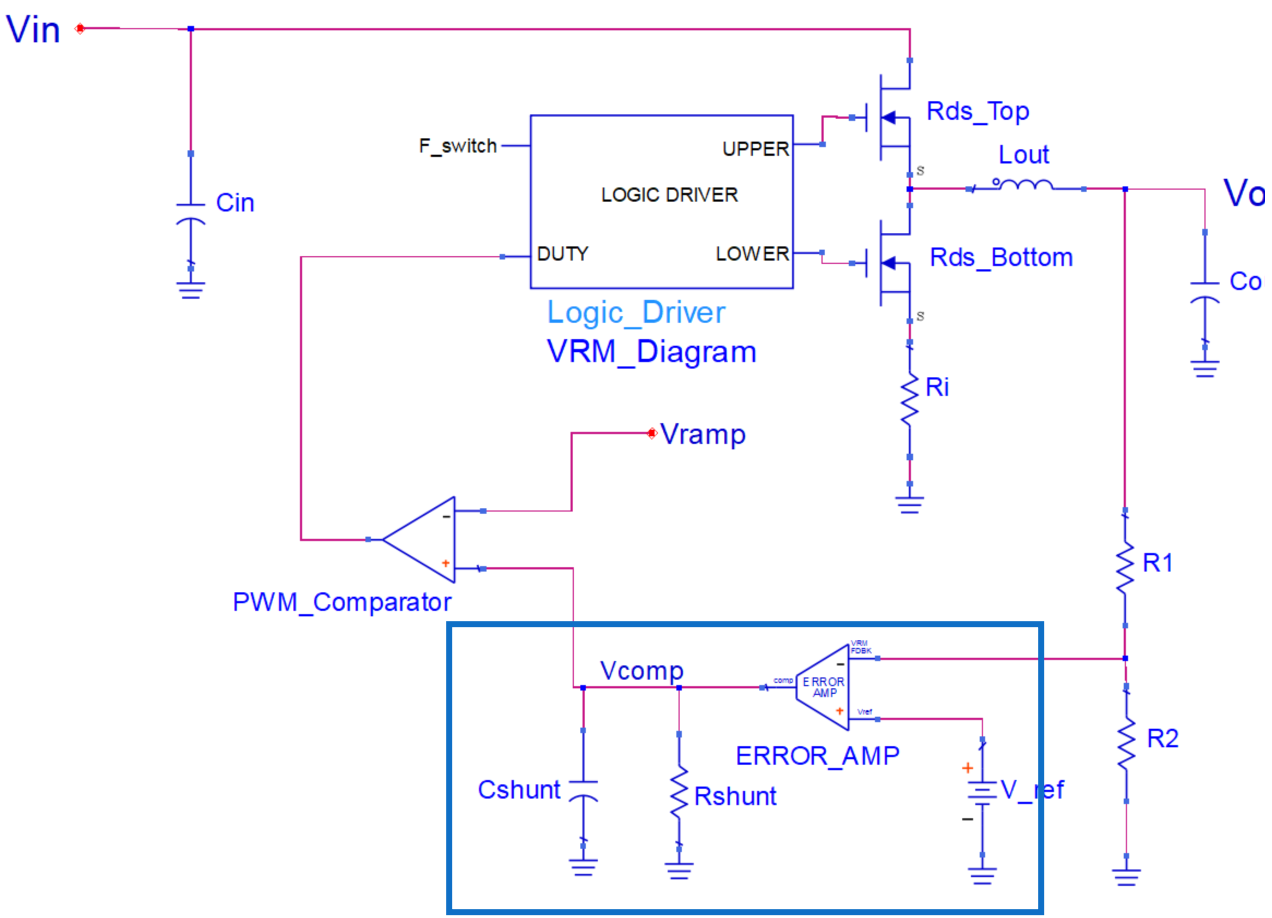
$$H(s) = H_1(s) \cdot H_2(s) \cdot H_3(s)$$

Transfer Function: $\mathrm{H(s)} = \frac{V_{comp}}{V_{out}} = \frac{R_2}{R_1+R_2} \cdot g_m \cdot \left( \frac{R_{shunt} \cdot \frac{1}{sC}}{R_{shunt} + \frac{1}{sC}} \right)$

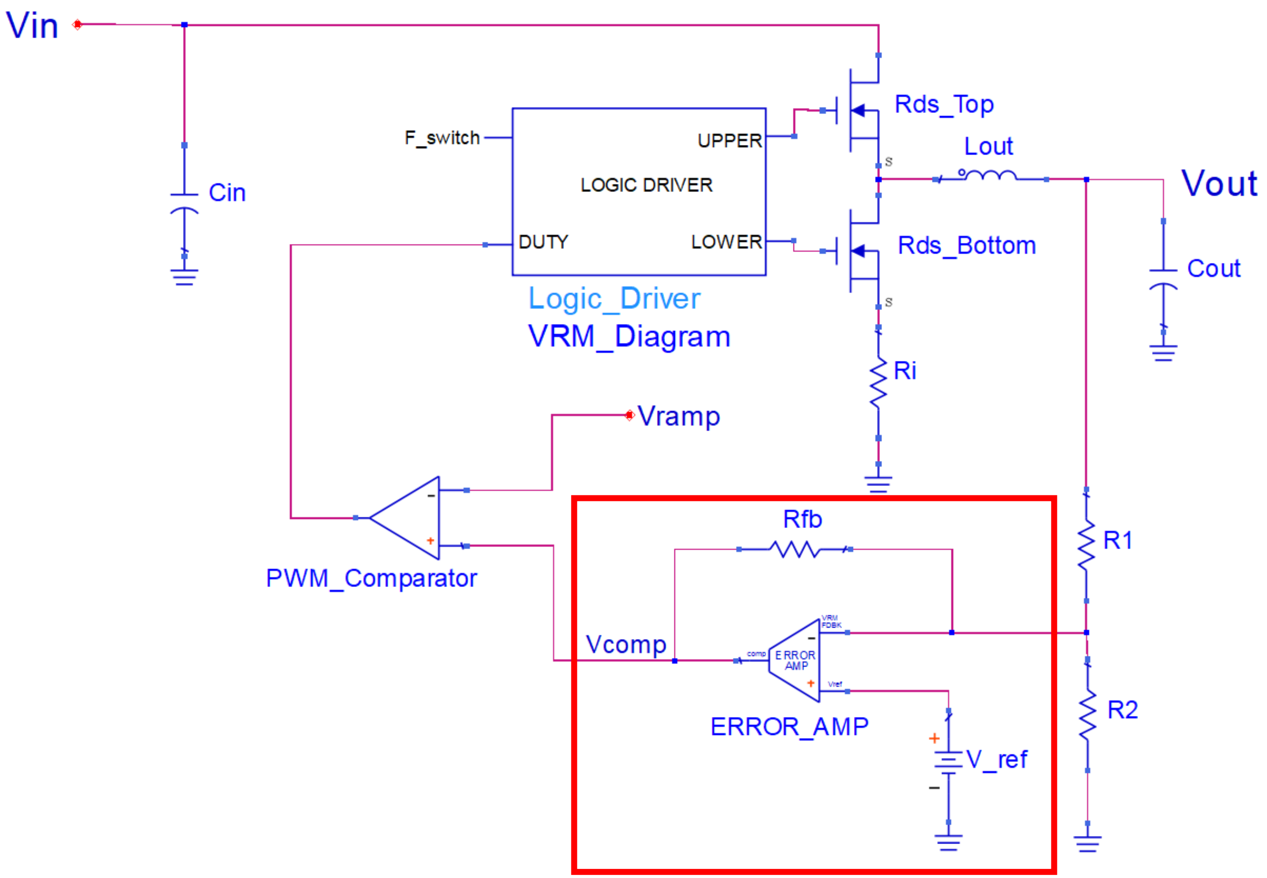
# Background on Transconductance Amplifiers

- A voltage-to-current converter, also called a Transconductance amplifier
  - Accepts input voltage $V_I$ and yields an output current of the type $i_o = g_m V_{in}$
  - Current mirror
- Transconductance amplifiers are also known as Error Amplifiers (EA) in the VRM
- These amplifiers have wide bandwidths and are inexpensive feedback amplifiers in a VRM
- This is, perhaps, the most common type of feedback amplifier in use today

# VRM Error Amp with Shunt vs. Series Compensation

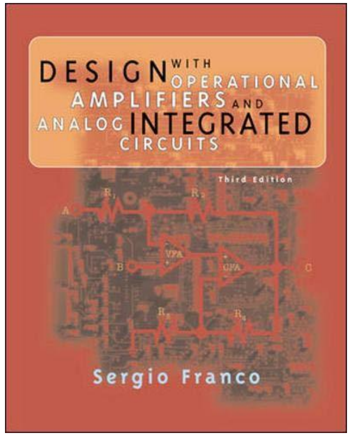


Error amplifier with **shunt** compensation



Error amplifier with **series** compensation

# Negative Feedback Amplifier Basics



Referenced from "Design with Operational Amplifiers and Analog Integrated Circuits by Sergio Franco"

An error amplifier accepts the signal $V_E$ and yields the output signal

$$V_o = \alpha V_E$$

A feedback network which samples the $V_o$ and produces a feedback signal is defined by:

$$V_{fb} = \beta V_o$$

Where the difference between the summing network is:

$$V_E = V_{in} - V_{fb} = V_{in} - \beta V_o$$

Eliminating $V_{fb}$ and $V_E$ and solving the equation for A = $V_o/V_{in}$ yields:

**Closed-loop Gain**

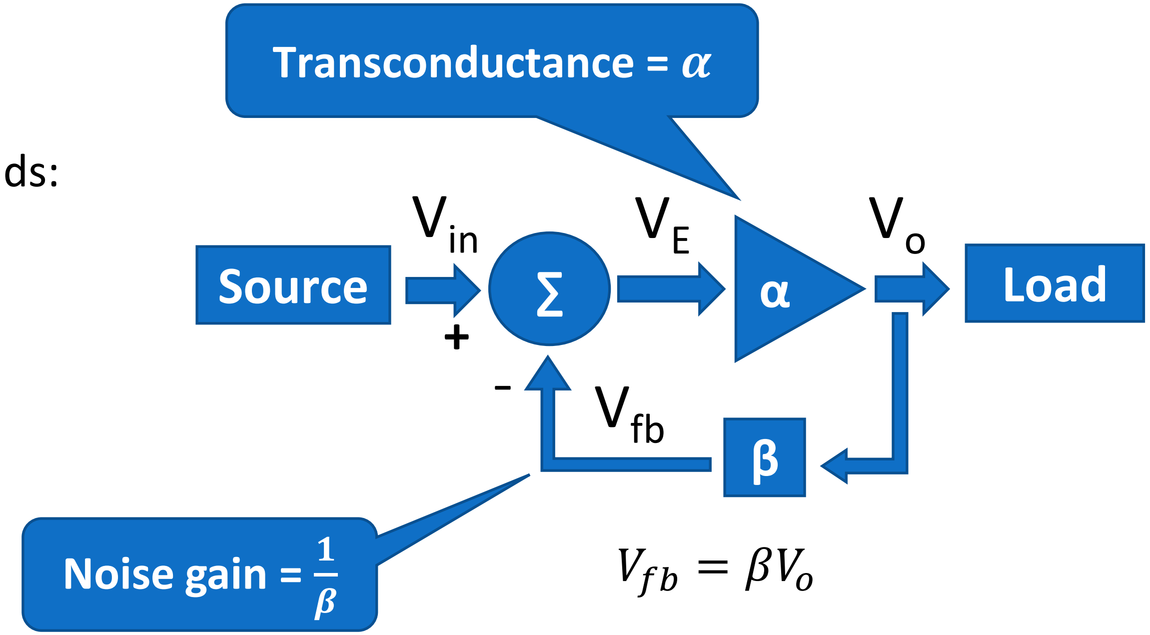
$$A = \frac{V_o}{V_{in}} = \frac{\alpha}{1+\alpha\beta}$$

Where our Loop Gain (T) or return ratio is defined by:

$$T = \alpha\beta$$

Where our desensitivity factor is defined by:

$$= 1 + \alpha\beta$$



$$V_{fb} = \beta V_o$$

# Gain Desensitivity with Feedback

Differentiating the closed-loop gain equation $\frac{\partial A}{\partial \alpha}$ yields:

$$\frac{\partial A}{\partial \alpha} = \frac{1}{(1+\alpha\beta)^2}$$

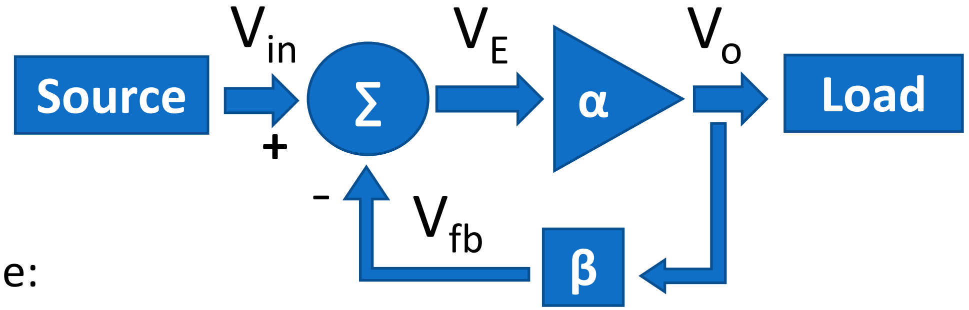
Since $1+\alpha\beta = A/\alpha$, we can rewrite and rearrange the above equation to be:

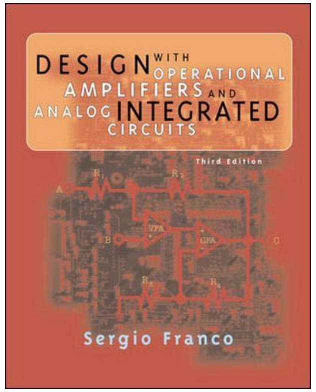
$$\frac{\partial A}{A} = \frac{1}{1+T} \cdot \frac{\partial \alpha}{\alpha}$$

Replacing differential with finite increments and multiplying both sides by 100, we can approximate:

$$100\frac{\Delta A}{A} \cong \frac{1}{1+T} \cdot (100\frac{\Delta \alpha}{\alpha})$$

For T sufficiently large, even a substantial change in α will cause an insignificant change in A





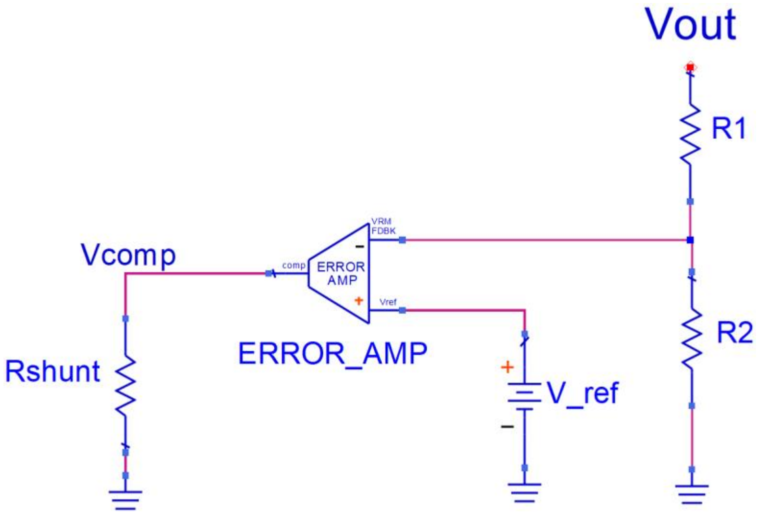
Referenced from “Design with Operational Amplifiers and Analog Integrated Circuits by Sergio Franco”

It becomes apparent that negative feedback desensitizes gain!

# Gain Insensitivity with Series Feedback

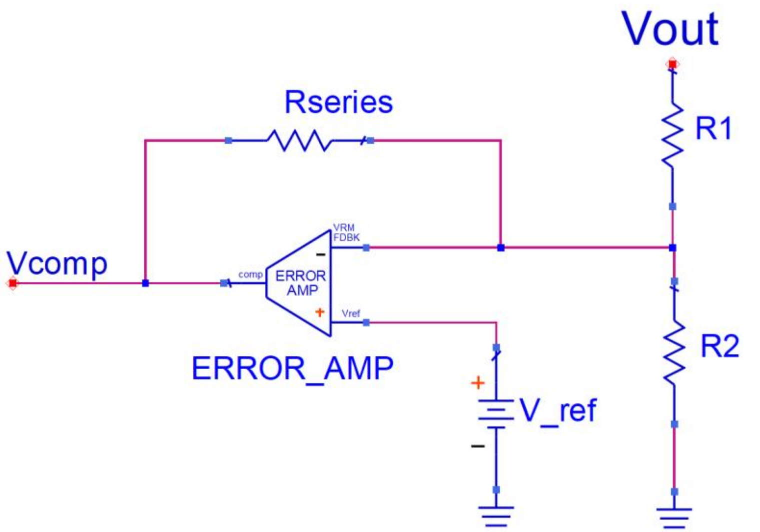
$$Av_{shunt} = \frac{R_2 \cdot G_m \cdot R_{shunt}}{R_1 + R_2}$$

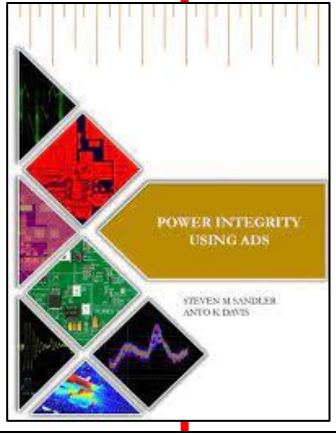
$$\frac{\partial Av_{shunt}}{\partial G_m} = \frac{R_2 \cdot R_{shunt}}{R_1 + R_2}$$



$$Av_{series} = \frac{R_2 \cdot (G_m \cdot R_{series} - 1)}{R_1 + R_2 + G_m \cdot R_1 \cdot R_2}$$

$$\frac{\partial Av_{series}}{\partial G_m} = \frac{R_2 \cdot R_{series}}{R_1 + R_2 + G_m \cdot R_1 \cdot R_2} - \frac{R_1 \cdot R_2^2 \cdot (G_m \cdot R_2 - 1)}{(R_1 + R_2 + G_m \cdot R_1 \cdot R_2)^2}$$





Referenced example from "Power Integrity Using ADS"

# Case Study

## Gain Sensitivity & Non-linear Distortion Reduction

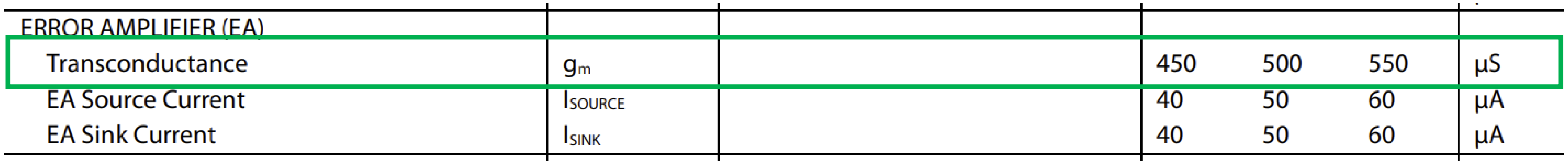
### *Shunt vs. Series Feedback Compensation*

| | VRM MPN | MFG | VRM Type | Compensation |
|---|---|---|---|---|
| CASE 1 | ADP2389 | Analog Devices | Current Mode | External |
| CASE 2 | ISL8026 | Renesas/Intersil | Current Mode | External or Internal** |
| CASE 3 | LM20143 | Texas Instruments | Current Mode | External |
| CASE 4 | TPS7H4003* | Texas Instruments | Current Mode | External |
| CASE 5 | MAX20098 | Maxim | Current Mode | External |

Note:
*Radiation-tolerant, designed for Space applications
**Internal compensation is set based on specific pin configuration. This EVAL used external compensation for this case study

# CASE 1 - ADP2389 Error Amplifier

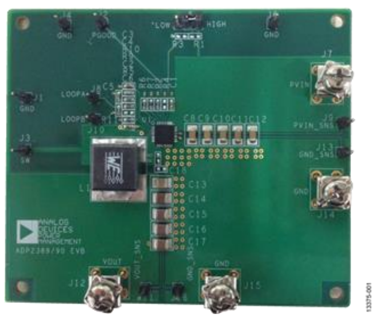
Per ADP2389 Datasheet

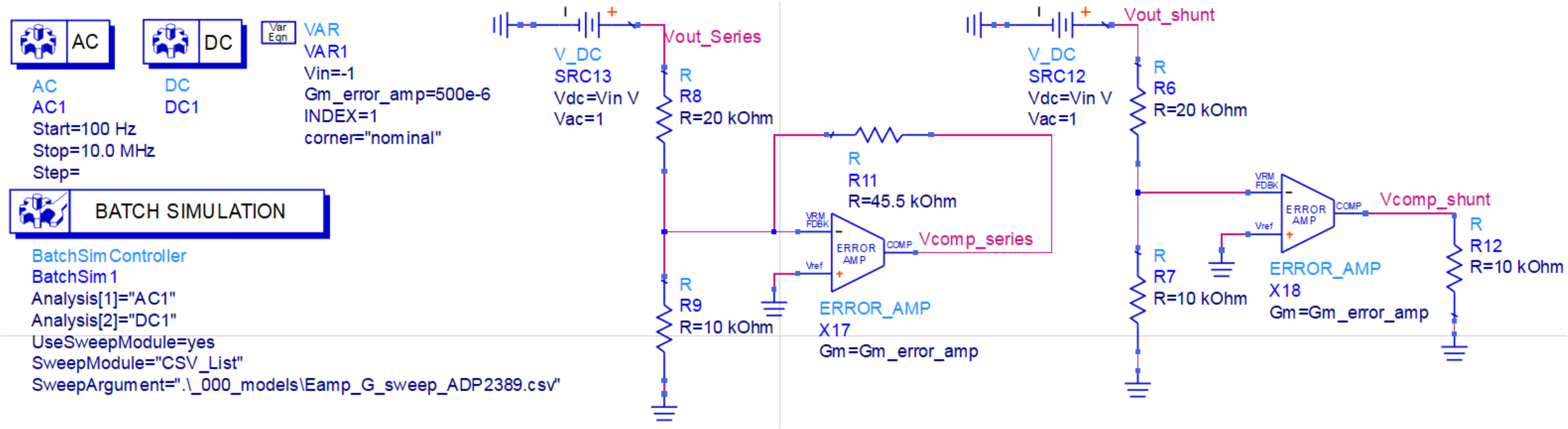


| | | | | | | |
|---|---|---|---|---|---|---|
| ERROR AMPLIFIER (EA) | | | | | | |
| Transconductance | $g_m$ | | 450 | 500 | 550 | µS |
| EA Source Current | $I_{SOURCE}$ | | 40 | 50 | 60 | µA |
| EA Sink Current | $I_{SINK}$ | | 40 | 50 | 60 | µA |

$Av_{shunt} = 1.67$

$Av_{series} = 1.67$





AC
AC1
Start=100 Hz
Stop=10.0 MHz
Step=

DC
DC1

VAR
VAR1
Vin=-1
Gm_error_amp=500e-6
INDEX=1
corner="nominal"

BatchSimController
BatchSim1
Analysis[1]="AC1"
Analysis[2]="DC1"
UseSweepModule=yes
SweepModule="CSV_List"
SweepArgument="._000_models\Eamp_G_sweep_ADP2389.csv"

V_DC
SRC13
Vdc=Vin V
Vac=1

R
R8
R=20 kOhm

R
R11
R=45.5 kOhm

R
R9
R=10 kOhm

ERROR_AMP
X17
Gm=Gm_error_amp

V_DC
SRC12
Vdc=Vin V
Vac=1

R
R6
R=20 kOhm

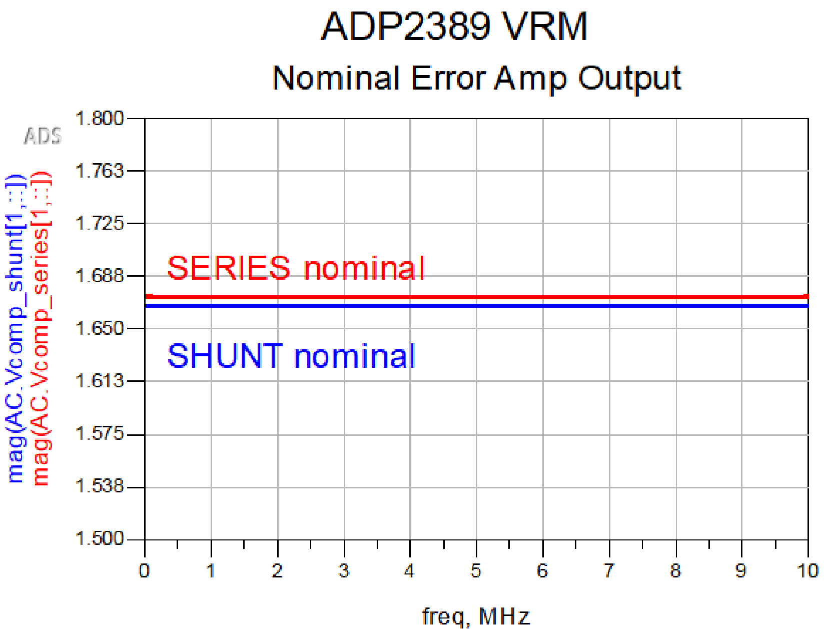
R
R7
R=10 kOhm

ERROR_AMP
X18
Gm=Gm_error_amp

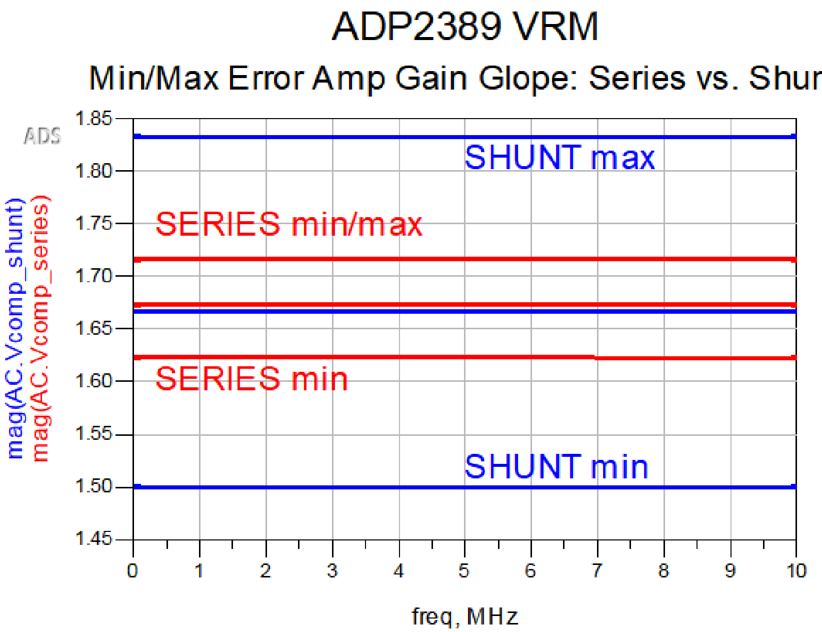
R
R12
R=10 kOhm

# CASE 1 - ADP2389 Error Amplifier **Vcomp Output**

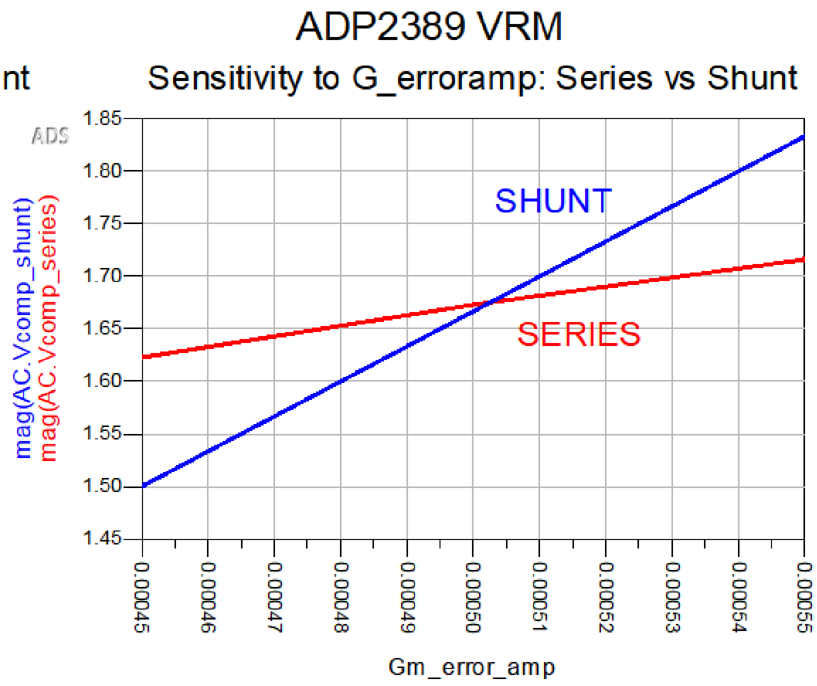
## Gain Sensitivity & Linear Distortion – Shunt vs. Series Feedback


ADP2389 VRM

Nominal Error Amp Output


ADP2389 VRM

Min/Max Error Amp Gain Glope: Series vs. Shunt


ADP2389 VRM

Sensitivity to G_erroramp: Series vs Shunt

This validates there is significantly greater sensitivity with shunt feedback

Series feedback is less sensitive to gain variation and exhibits less linear distortion

# CASE 2 - ISL8026 Error Amplifier

Per ISL8026
Datasheet

| | | | | | | |
|---|---|---|---|---|---|---|
| **COMPENSATION** | | | | | | |
| Error Amplifier Transconductance | | Internal compensation | | 60 | | µA/V |
| | | External compensation | | 120 | | µA/V |

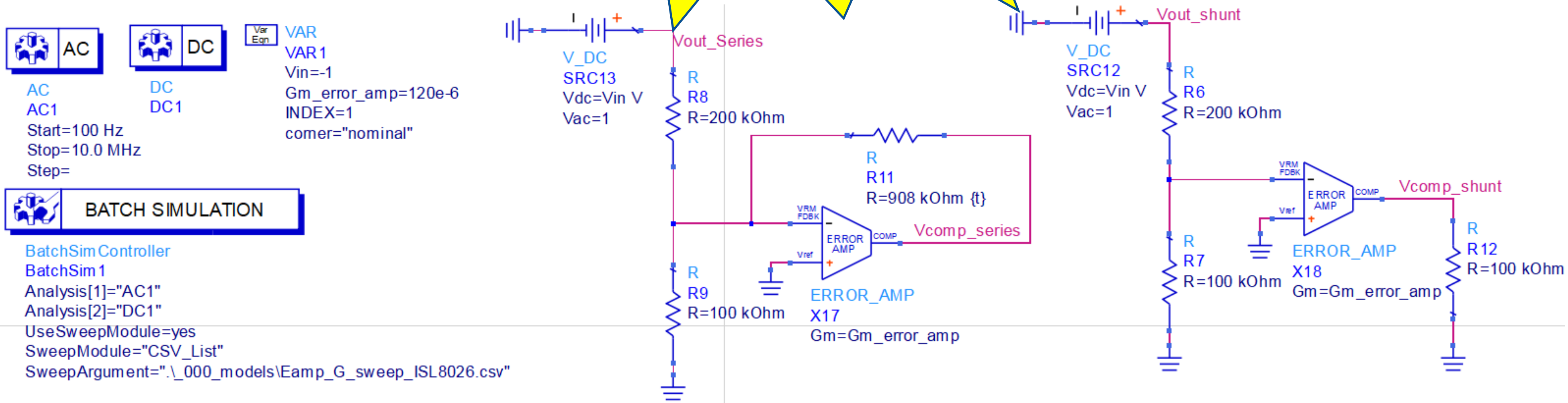
Assume +/=50% variation
Min = 60 uA/V, Max = 180 uA/V

**Gm tolerance is a HUGE performance factor**

Many VRM datasheets do not include the Gm tolerances

$Av_{shunt} = 4$

$Av_{series} = 4$



AC
AC1
Start=100 Hz
Stop=10.0 MHz
Step=

DC
DC1

VAR
VAR1
Vin=-1
Gm_error_amp=120e-6
INDEX=1
corner="nominal"

BatchSimController
BatchSim1
Analysis[1]="AC1"
Analysis[2]="DC1"
UseSweepModule=yes
SweepModule="CSV_List"
SweepArgument="._000_models\Eamp_G_sweep_ISL8026.csv"

V_DC
SRC13
Vdc=Vin V
Vac=1

R
R8
R=200 kOhm

R
R9
R=100 kOhm

R
R11
R=908 kOhm {t}

ERROR_AMP
X17
Gm=Gm_error_amp

V_DC
SRC12
Vdc=Vin V
Vac=1

R
R6
R=200 kOhm

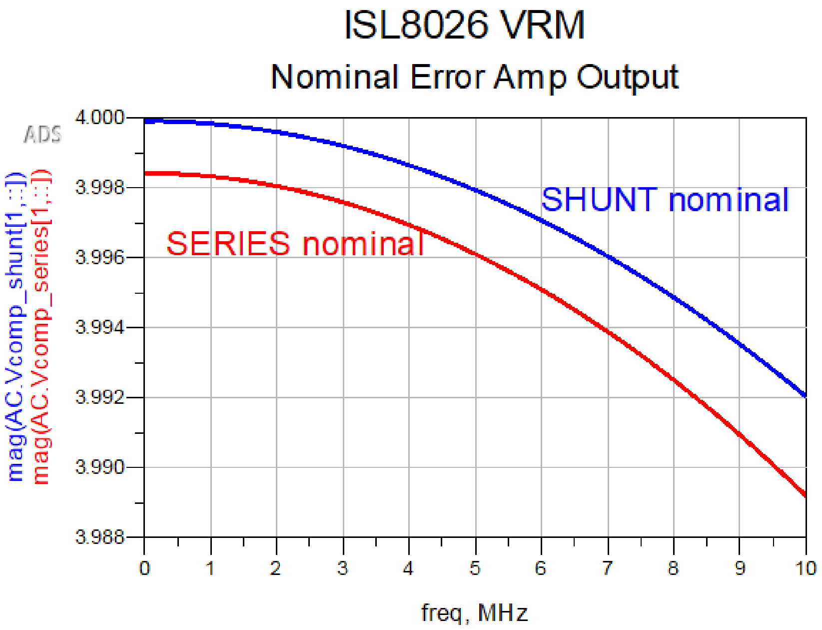
R
R7
R=100 kOhm

ERROR_AMP
X18
Gm=Gm_error_amp

R
R12
R=100 kOhm

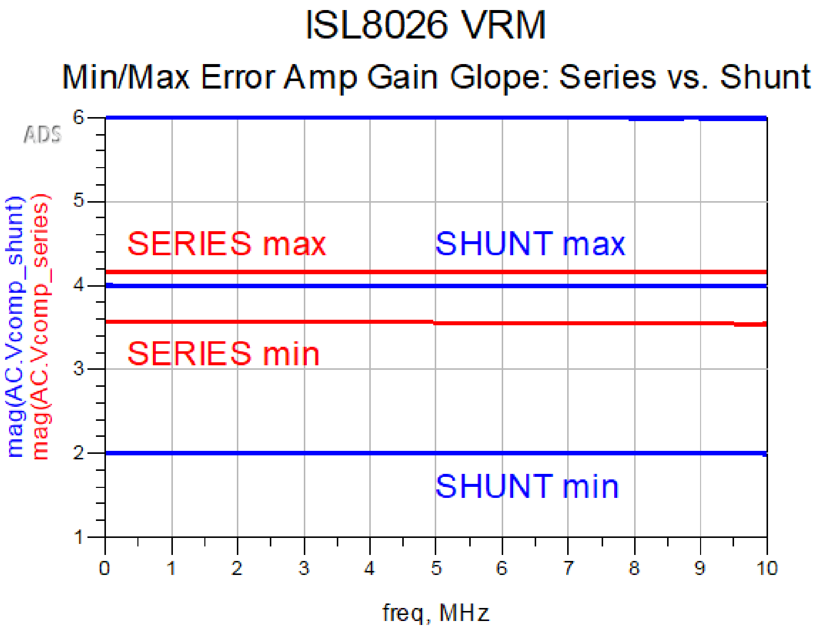
# CASE 2 - ISL8026 Error Amplifier **Vcomp Output**

## Gain Sensitivity & Linear Distortion – Shunt vs. Series Feedback



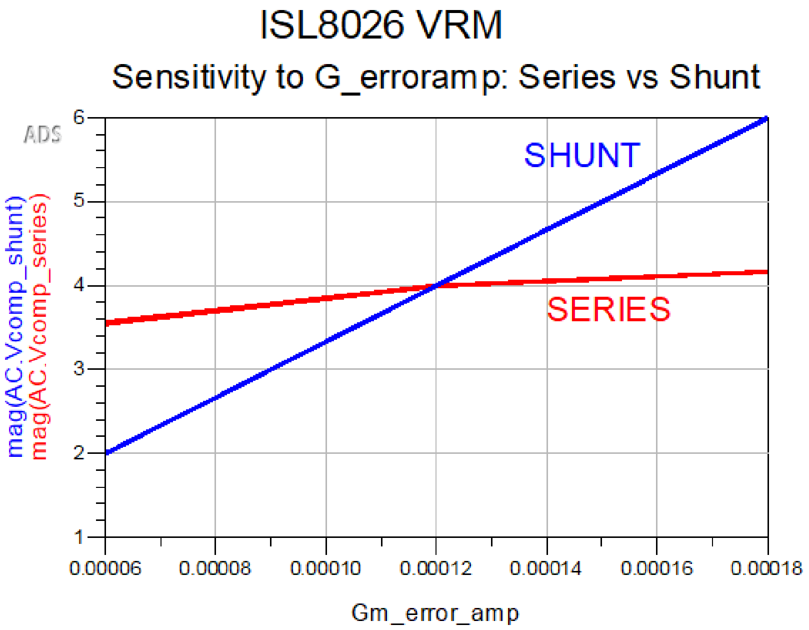
ISL8026 VRM

Nominal Error Amp Output



ISL8026 VRM

Min/Max Error Amp Gain Glope: Series vs. Shunt



ISL8026 VRM

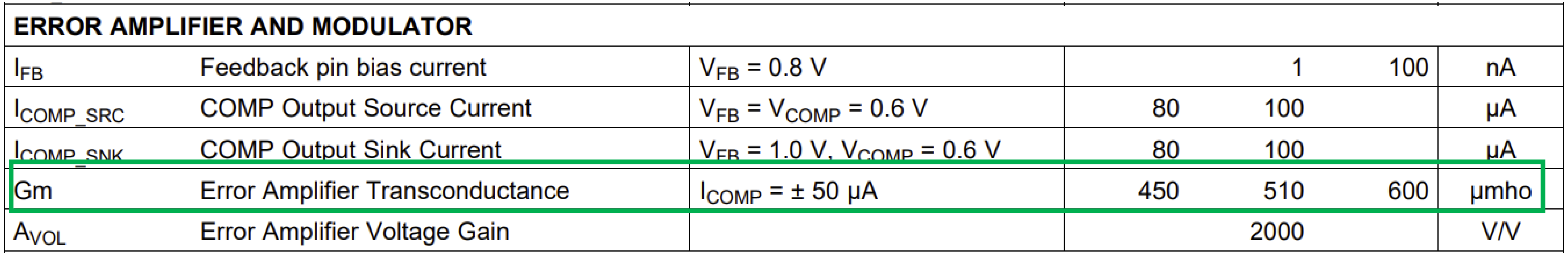
Sensitivity to G_erroramp: Series vs Shunt

This validates there is significantly greater sensitivity with shunt feedback

Series feedback is less sensitive to gain variation and exhibits less linear distortion

# CASE 3 - LM20143 Error Amplifier

Per LM20143 Datasheet

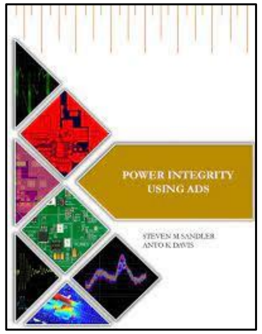


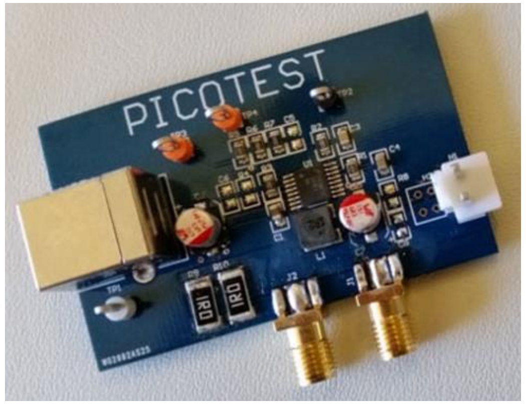
| ERROR AMPLIFIER AND MODULATOR | | | | | | |
|---|---|---|---|---|---|---|
| $I_{FB}$ | Feedback pin bias current | $V_{FB}$ = 0.8 V | | 1 | 100 | nA |
| $I_{COMP\_SRC}$ | COMP Output Source Current | $V_{FB} = V_{COMP}$ = 0.6 V | 80 | 100 | | µA |
| $I_{COMP\_SNK}$ | COMP Output Sink Current | $V_{FB}$ = 1.0 V, $V_{COMP}$ = 0.6 V | 80 | 100 | | µA |
| Gm | Error Amplifier Transconductance | $I_{COMP}$ = ± 50 µA | 450 | 510 | 600 | µmho |
| $A_{VOL}$ | Error Amplifier Voltage Gain | | | 2000 | | V/V |

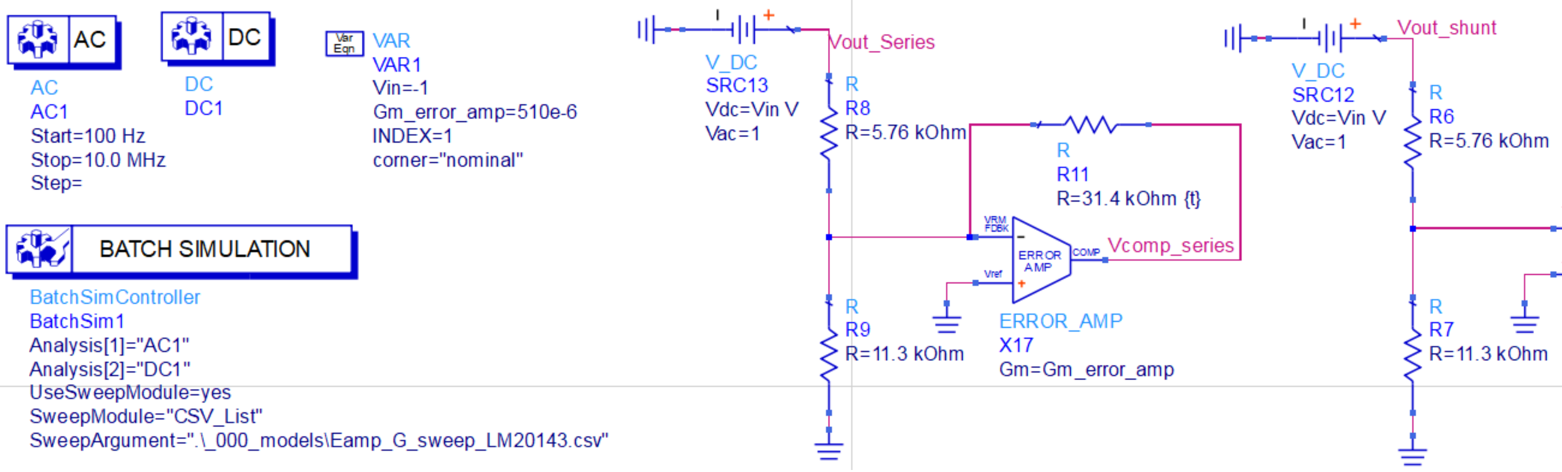
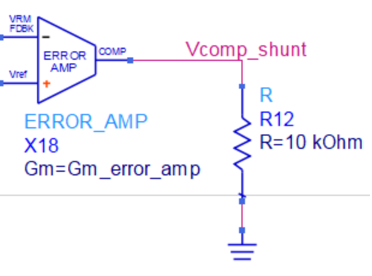
$Av_{shunt} = 3.38$

$Av_{series} = 3.38$

Referenced example from
“Power Integrity Using ADS”





AC
AC1
Start=100 Hz
Stop=10.0 MHz
Step=

DC
DC1

VAR
VAR1
Vin=-1
Gm_error_amp=510e-6
INDEX=1
corner="nominal"

BATCH SIMULATION
BatchSimController
BatchSim1
Analysis[1]="AC1"
Analysis[2]="DC1"
UseSweepModule=yes
SweepModule="CSV_List"
SweepArgument="._000_models\Eamp_G_sweep_LM20143.csv"

V_DC
SRC13
Vdc=Vin V
Vac=1

R
R8
R=5.76 kOhm

R
R11
R=31.4 kOhm {t}

R
R9
R=11.3 kOhm

ERROR_AMP
X17
Gm=Gm_error_amp

V_DC
SRC12
Vdc=Vin V
Vac=1

R
R6
R=5.76 kOhm

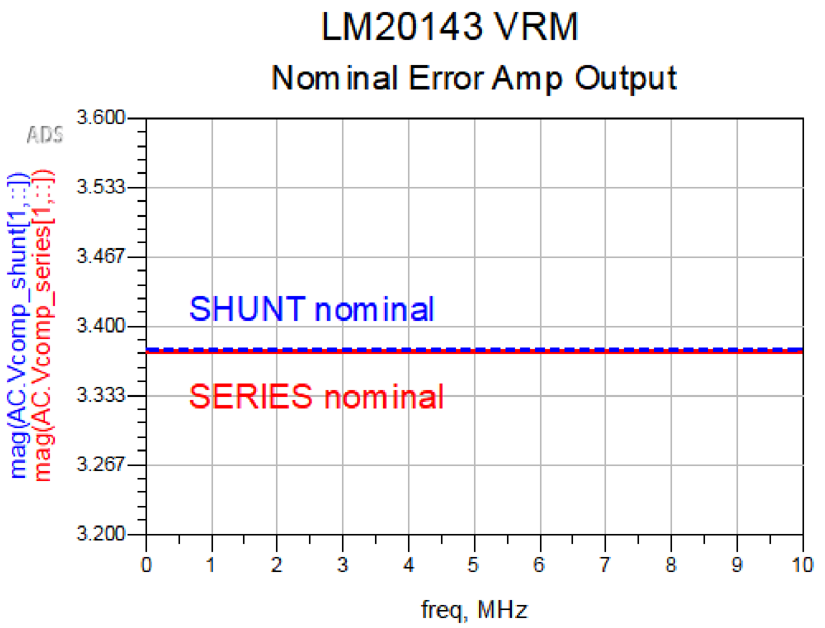
R
R7
R=11.3 kOhm

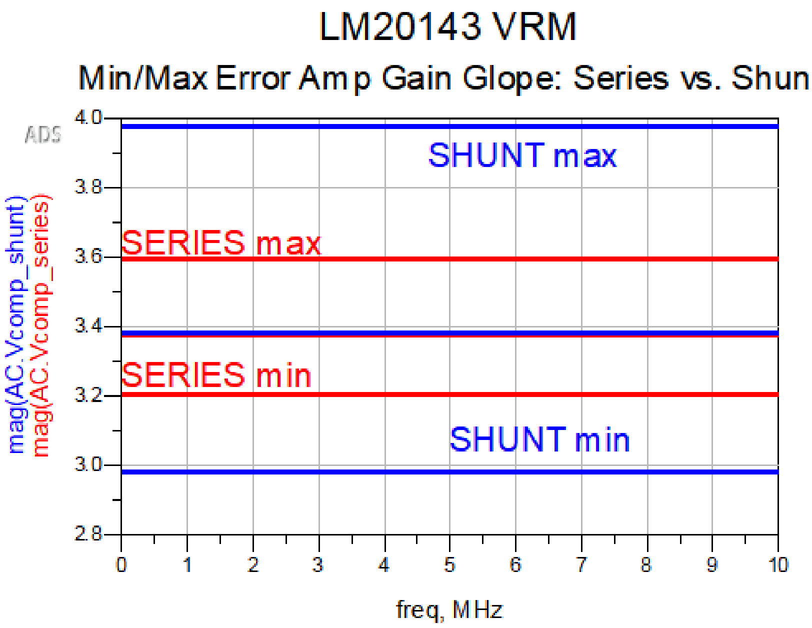
ERROR_AMP
X18
Gm=Gm_error_amp

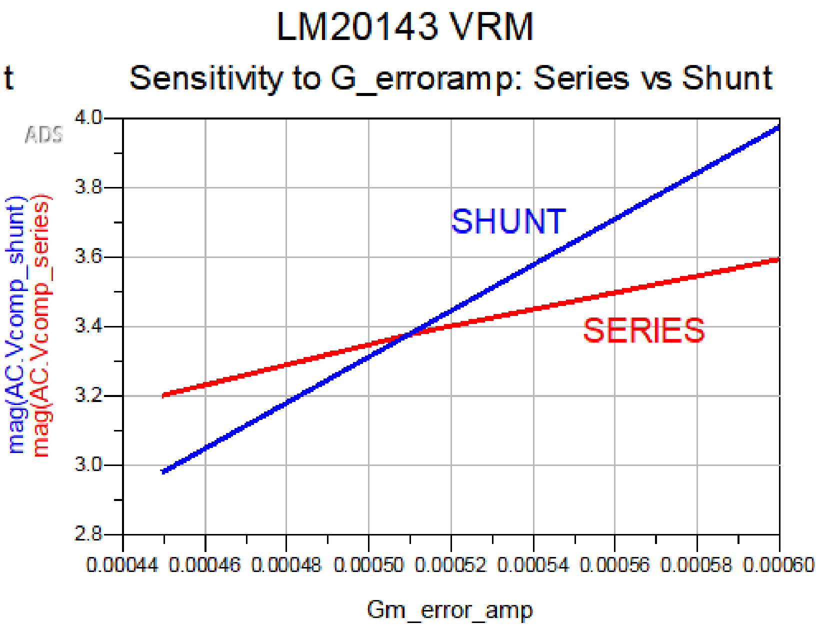
R
R12
R=10 kOhm

# CASE 3 - LM20143 Error Amplifier **Vcomp Output**

## Gain Sensitivity & Linear Distortion – Shunt vs. Series Feedback





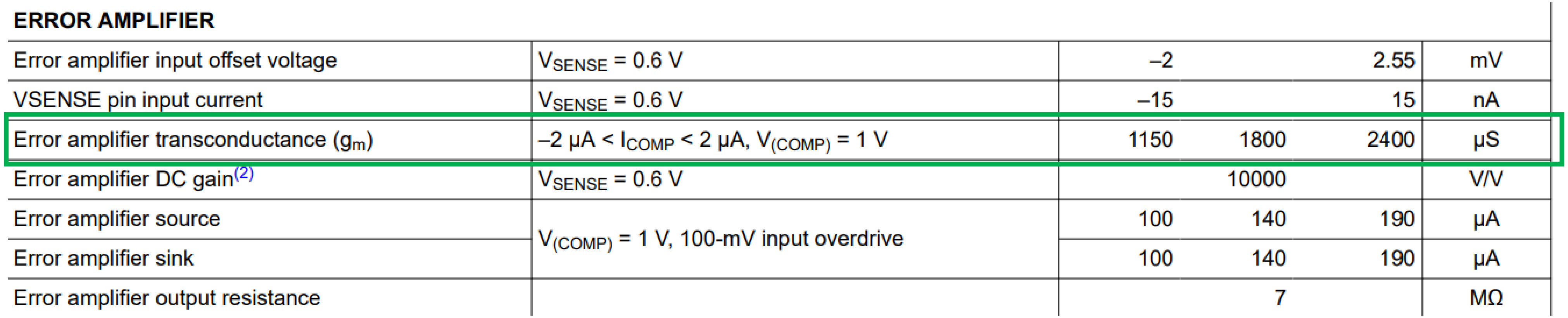


This validates there is significantly greater sensitivity with shunt feedback

Series feedback is less sensitive to gain variation and exhibits less linear distortion

# CASE 4 - TPS7H4003 Error Amplifier

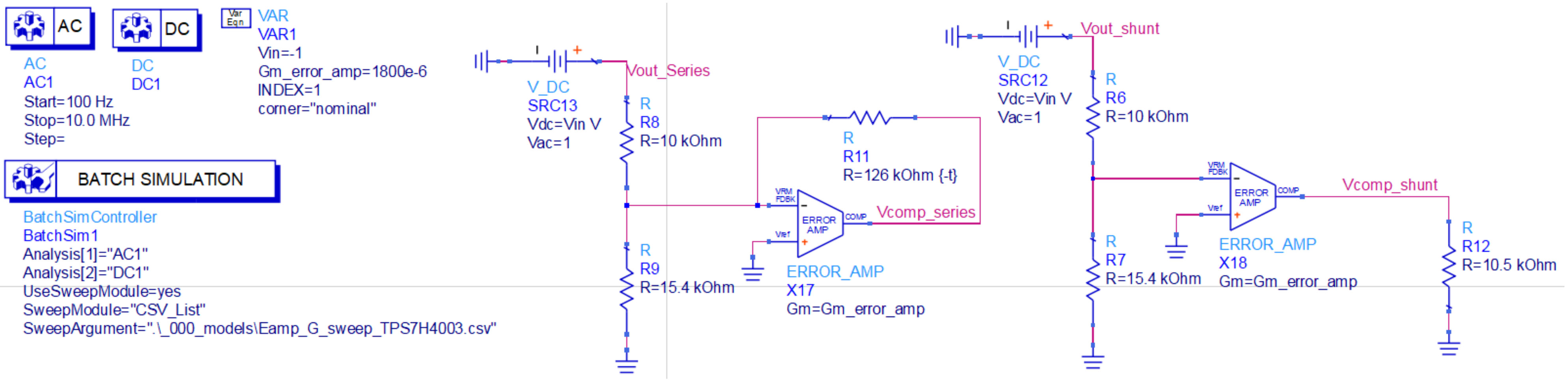
Per TPS7H4003 Datasheet



| | | | | | |
|---|---|---|---|---|---|
| **ERROR AMPLIFIER** | | | | | |
| Error amplifier input offset voltage | $V_{SENSE}$ = 0.6 V | –2 | | 2.55 | mV |
| VSENSE pin input current | $V_{SENSE}$ = 0.6 V | –15 | | 15 | nA |
| Error amplifier transconductance ($g_m$) | –2 µA < $I_{COMP}$ < 2 µA, $V_{(COMP)}$ = 1 V | 1150 | 1800 | 2400 | µS |
| Error amplifier DC gain[(2)] | $V_{SENSE}$ = 0.6 V | | 10000 | | V/V |
| Error amplifier source | $V_{(COMP)}$ = 1 V, 100-mV input overdrive | 100 | 140 | 190 | µA |
| Error amplifier sink | | 100 | 140 | 190 | µA |
| Error amplifier output resistance | | | 7 | | MΩ |

$Av_{shunt} = 11.5$

$Av_{series} = 11.5$



AC
AC1
Start=100 Hz
Stop=10.0 MHz
Step=

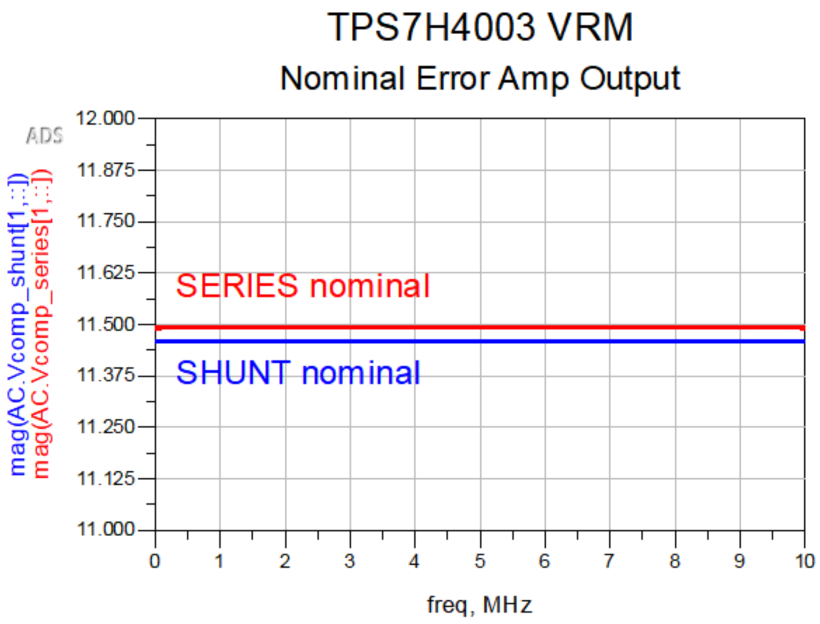
DC
DC1

VAR
VAR1
Vin=-1
Gm_error_amp=1800e-6
INDEX=1
corner="nominal"

BATCH SIMULATION
BatchSimController
BatchSim1
Analysis[1]="AC1"
Analysis[2]="DC1"
UseSweepModule=yes
SweepModule="CSV_List"
SweepArgument="._000_models\Eamp_G_sweep_TPS7H4003.csv"

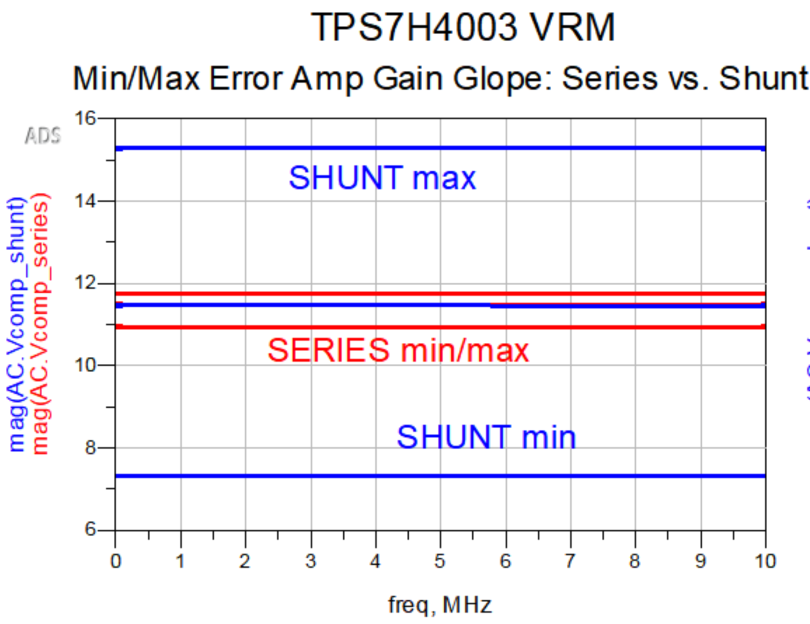
# CASE 4 - TPS7H4003 Error Amplifier **Vcomp Output**

## Gain Sensitivity & Linear Distortion – Shunt vs. Series Feedback



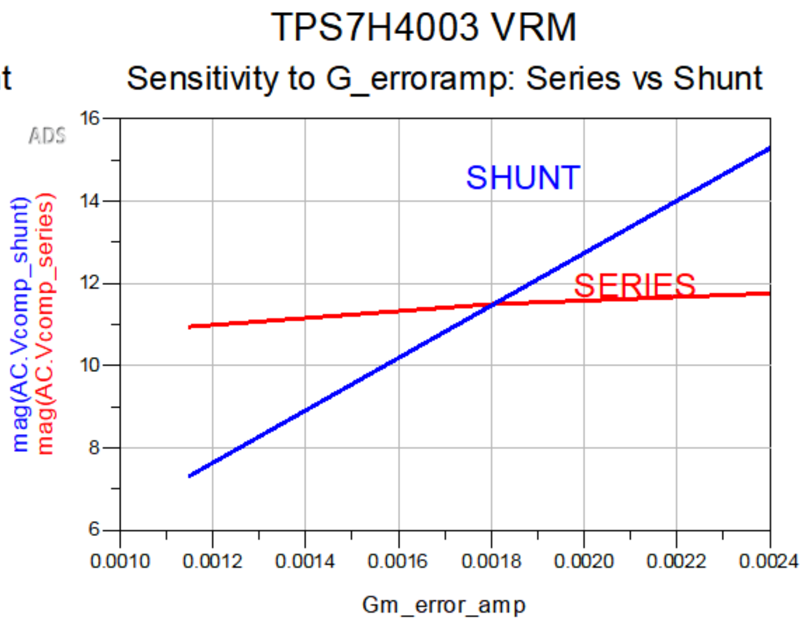
TPS7H4003 VRM

Nominal Error Amp Output



TPS7H4003 VRM

Min/Max Error Amp Gain Glope: Series vs. Shunt



TPS7H4003 VRM

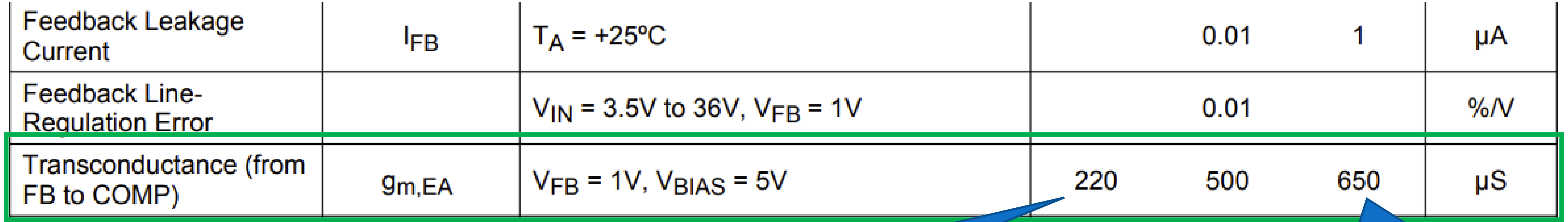
Sensitivity to G_erroramp: Series vs Shunt

This validates there is significantly greater sensitivity with shunt feedback

Series feedback is less sensitive to gain variation and exhibits less linear distortion

# CASE 5 - MAX20098 Error Amplifier

Per MAX20098 Datasheet



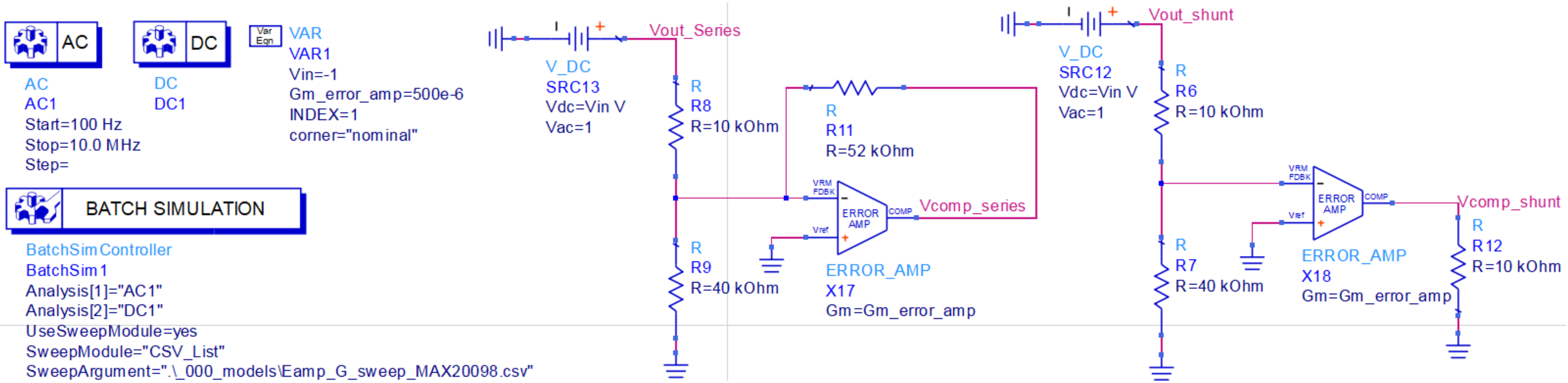
| | | | | | | |
|---|---|---|---|---|---|---|
| Feedback Leakage Current | $I_{FB}$ | $T_A$ = +25°C | | 0.01 | 1 | µA |
| Feedback Line-Regulation Error | | $V_{IN}$ = 3.5V to 36V, $V_{FB}$ = 1V | | 0.01 | | %/V |
| Transconductance (from FB to COMP) | $g_{m,EA}$ | $V_{FB}$ = 1V, $V_{BIAS}$ = 5V | 220 | 500 | 650 | µS |

**-44% variation from nominal**

**+50% variation from nominal**

$Av_{shunt} = 4$

$Av_{series} = 4$



AC
AC1
Start=100 Hz
Stop=10.0 MHz
Step=

DC
DC1

VAR
VAR1
Vin=-1
Gm_error_amp=500e-6
INDEX=1
corner="nominal"

BatchSimController
BatchSim1
Analysis[1]="AC1"
Analysis[2]="DC1"
UseSweepModule=yes
SweepModule="CSV_List"
SweepArgument="._000_models\Eamp_G_sweep_MAX20098.csv"

V_DC
SRC13
Vdc=Vin V
Vac=1

R
R8
R=10 kOhm

R
R9
R=40 kOhm

R
R11
R=52 kOhm

ERROR_AMP
X17
Gm=Gm_error_amp

V_DC
SRC12
Vdc=Vin V
Vac=1

R
R6
R=10 kOhm

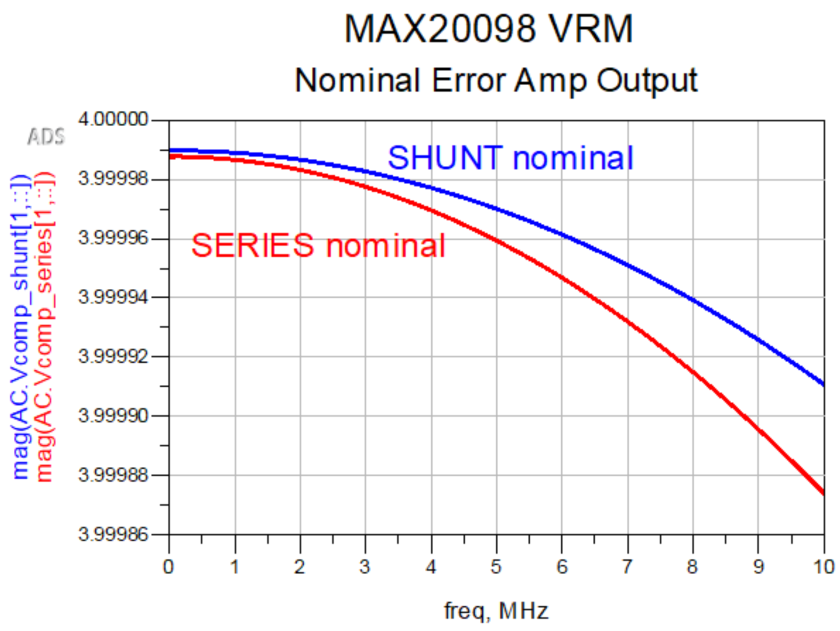
R
R7
R=40 kOhm

ERROR_AMP
X18
Gm=Gm_error_amp

R
R12
R=10 kOhm

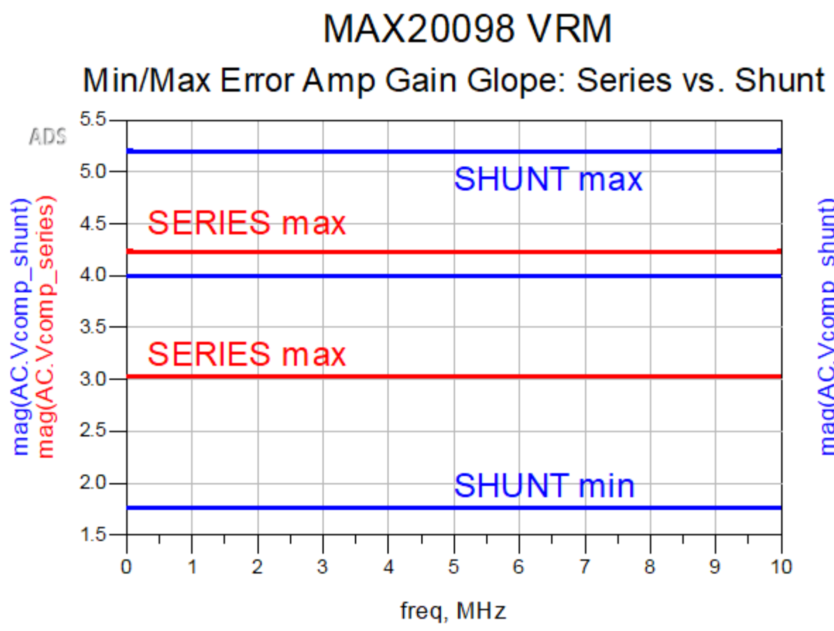
# CASE 5 - MAX20098 Error Amplifier **Vcomp Output**

## Gain Sensitivity & Linear Distortion – Shunt vs. Series Feedback



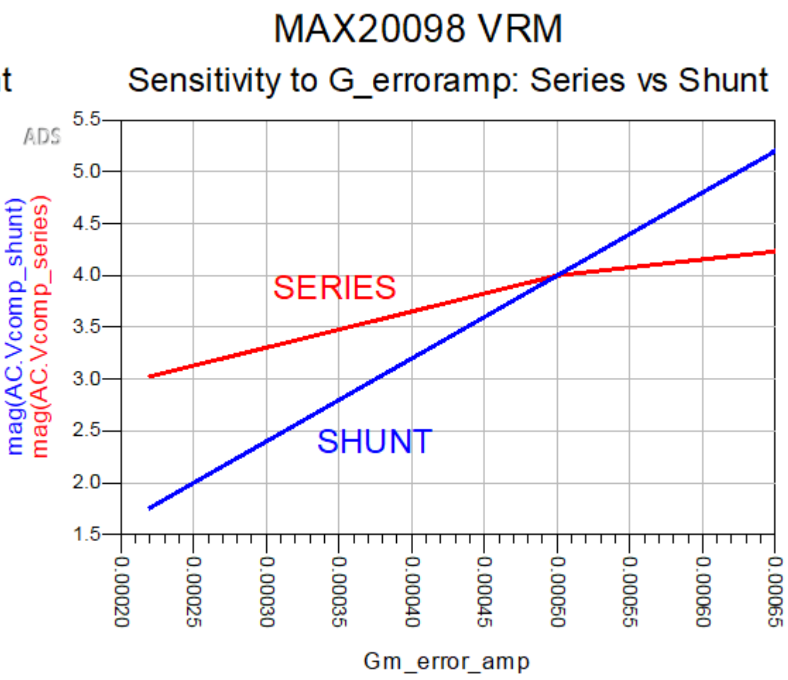
MAX20098 VRM

Nominal Error Amp Output



MAX20098 VRM

Min/Max Error Amp Gain Glope: Series vs. Shunt



MAX20098 VRM

Sensitivity to G_erroramp: Series vs Shunt

This validates there is significantly greater sensitivity with shunt feedback

Series feedback is less sensitive to gain variation and exhibits less linear distortion

# Case Study using the Sandler State-Space Average Model

## VRM Output Impedance and Stability Analysis

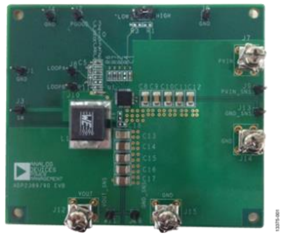
### *Shunt vs. Series Feedback Compensation*

| | VRM MPN | MFG | VRM Type | Compensation |
|---|---|---|---|---|
| CASE 1 | ADP2389 | Analog Devices | Current Mode | External |
| CASE 2 | ISL8026 | Renesas/Intersil | Current Mode | External or Internal** |
| CASE 3 | LM20143 | Texas Instruments | Current Mode | External |
| CASE 4 | TPS7H4003* | Texas Instruments | Current Mode | External |
| CASE 5 | MAX20098 | Maxim | Current Mode | External |

Notes:
*Radiation-tolerant, designed for Space applications
**Internal compensation is set based on specific pin configuration. This EVAL used external compensation for this case study

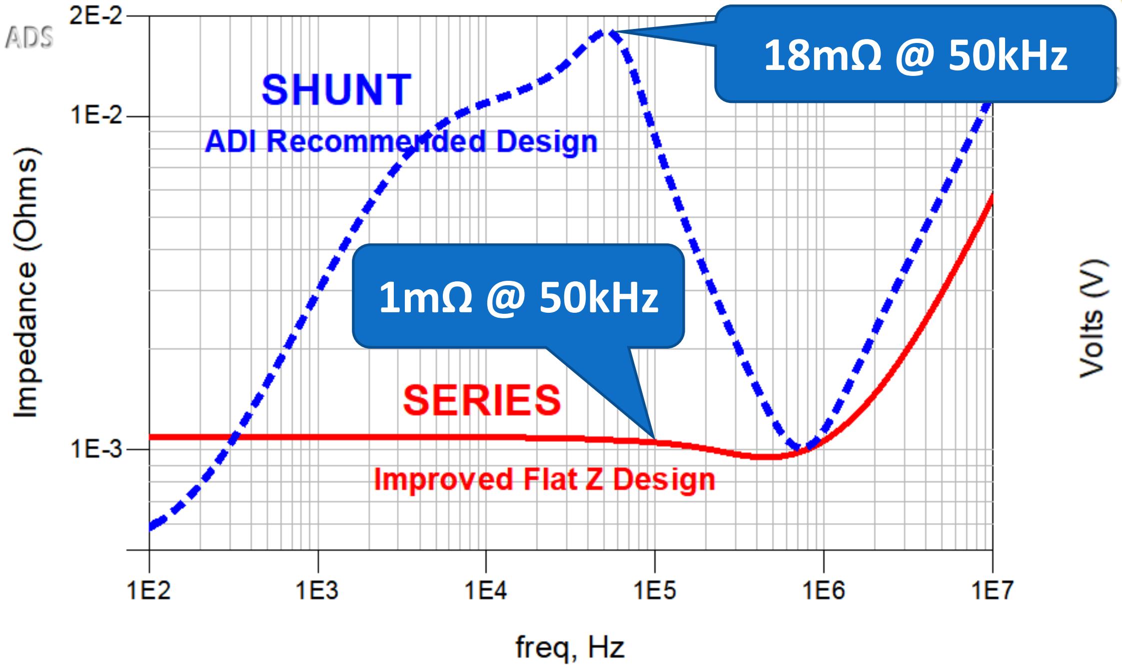
# CASE 1 - ADP2389 Output Impedance & Step Load Response

## Shunt vs. Series Compensation



ADP2389 EVAL

VRM Output Impedance - Shunt vs. Series Compensation



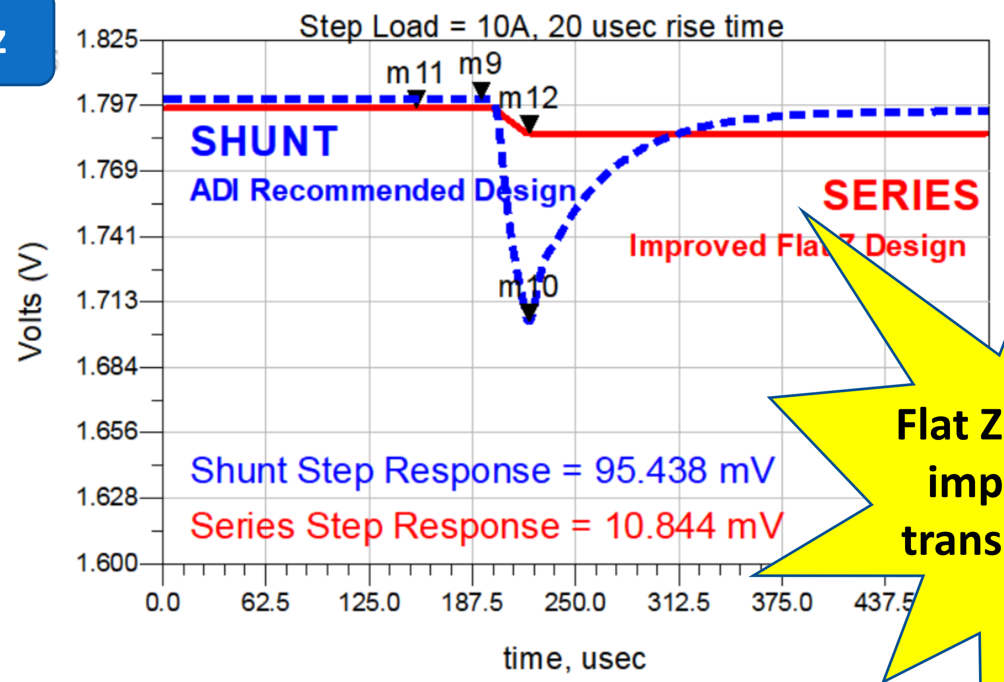
18mΩ @ 50kHz

1mΩ @ 50kHz

$R_{series} = 2.3M\Omega$

ADP2389 EVAL

VRM Step Load Response - Shunt vs. Series Compensation



Shunt Step Response = 95.438 mV

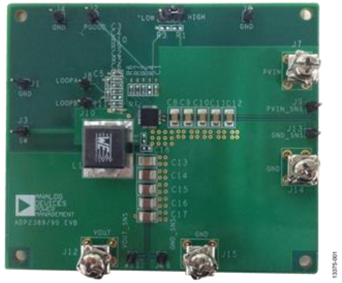
Series Step Response = 10.844 mV

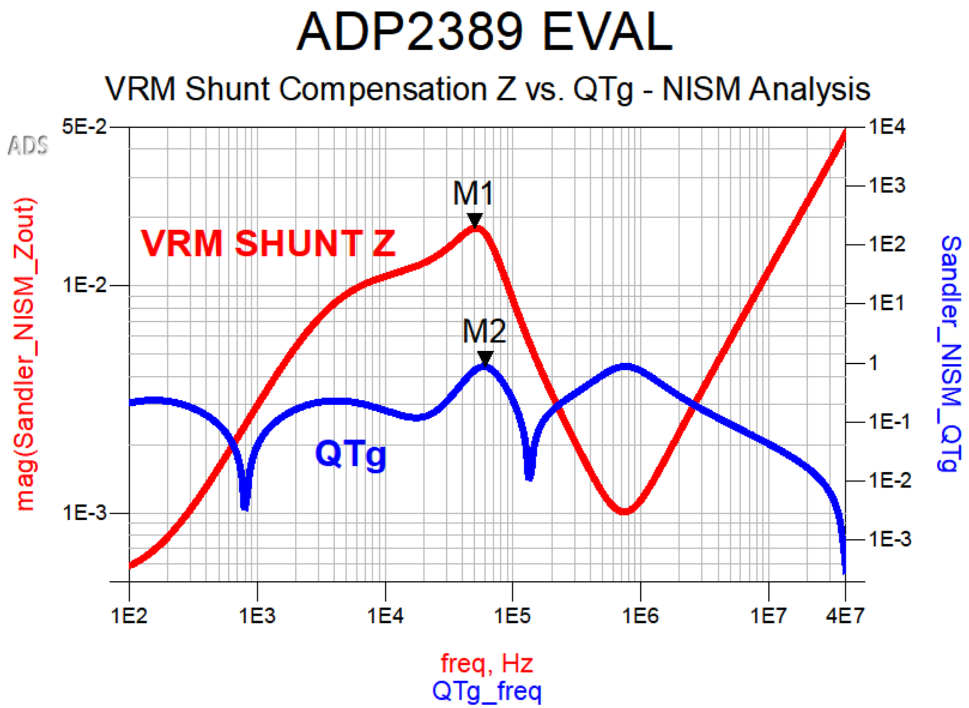
**Flat Z means 88.6% improvement in transient response**

Series compensation allows VRM output Z to be flat -> Better Transient Response

# CASE 1 - ADP2389 Stability Analysis with NISM

## Shunt vs. Series Compensation

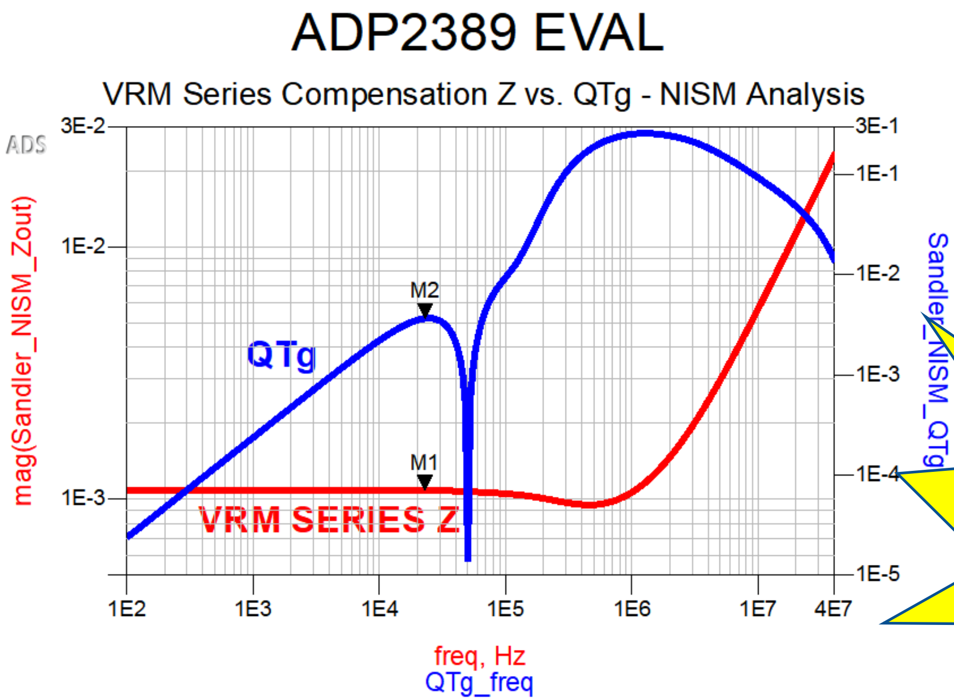




ADP2389 EVAL

VRM Shunt Compensation Z vs. QTg - NISM Analysis

**Sandler_NISM_PM: 56.988 degrees**
**Z Frequency: 50233.474 Hz**
**Q Frequency: 60398.011 Hz**
**Effective Q: 0.867**



ADP2389 EVAL

VRM Series Compensation Z vs. QTg - NISM Analysis

**Sandler_NISM_PM: >71 degrees**
**Z Frequency: 22954.516 Hz**
**Q Frequency: 22954.516 Hz**
**Effective Q: 0.004**

**Flat Z means 99.5% reduction of Q**

**$R_{series} = 2.3M\Omega$**

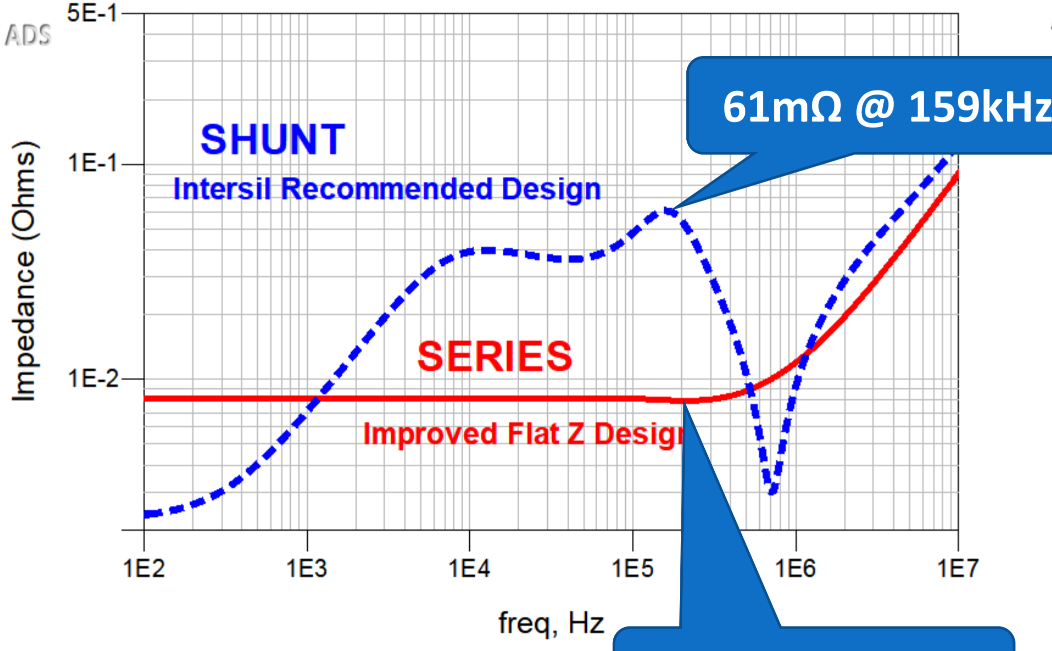
***Non-Invasive Stability Measurement (NISM)**

# CASE 2 - ISL8026 Output Impedance & Step Load Response

## Shunt vs. Series

ISL8026 EVAL

VRM Output Impedance - Shunt vs. Series Compensation



61mΩ @ 159kHz

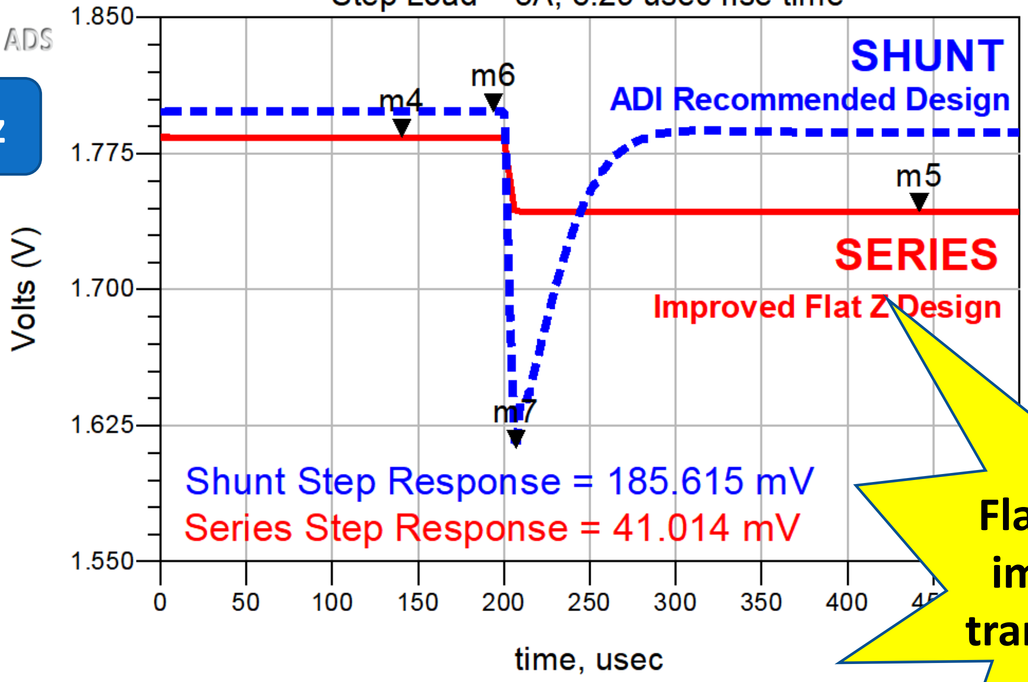
8mΩ @ 159kHz

$R_{series}$ = 4MΩ

ISL8026 EVAL

VRM Step Load Response - Shunt vs. Series Compensation

Step Load = 5A, 6.29 usec rise time



Shunt Step Response = 185.615 mV

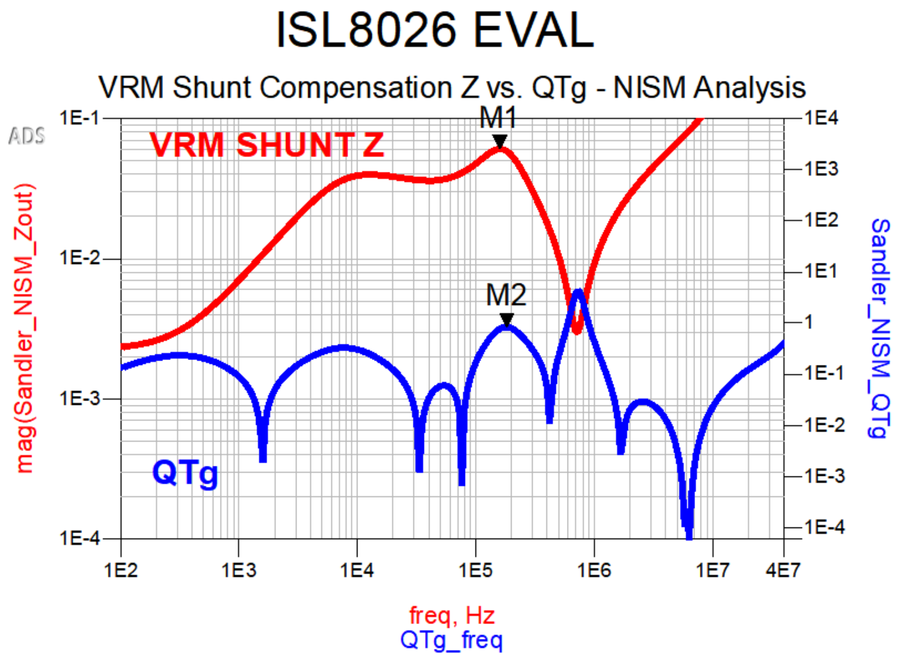
Series Step Response = 41.014 mV

**Flat Z means 77% improvement in transient response**

Series compensation allows VRM output Z to be flat -> Better Transient Response

# CASE 2 - ISL8026 Stability Analysis with NISM

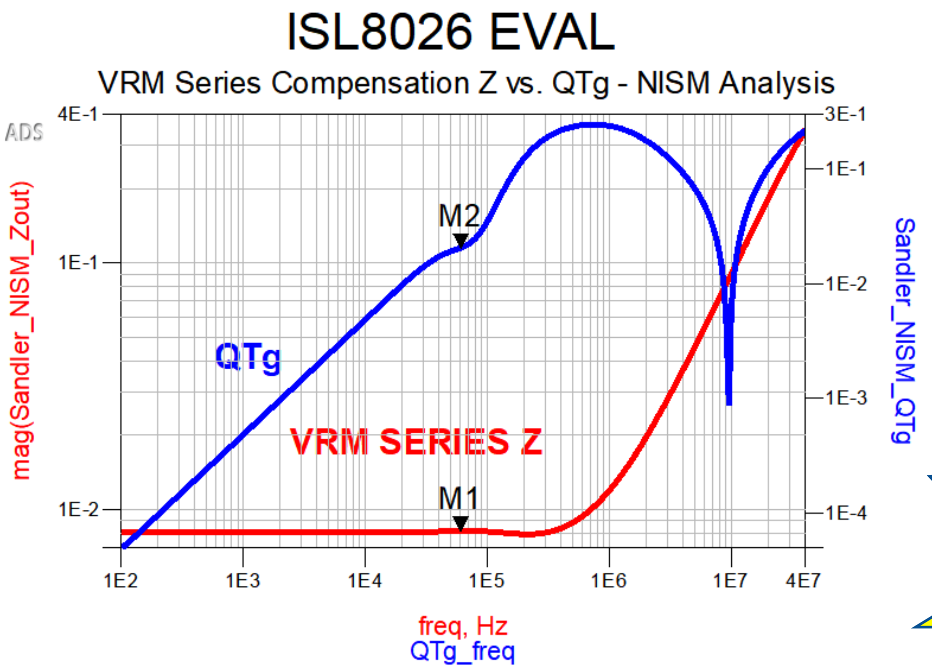
## Shunt vs. Series


ISL8026 EVAL

VRM Shunt Compensation Z vs. QTg - NISM Analysis

**Sandler_NISM_PM: 57.150 degrees**
**Z Frequency: 158919.481 Hz**
**Q Frequency: 182473.251 Hz**
**Effective Q: 0.836**

**$R_{series} = 4M\Omega$**


ISL8026 EVAL

VRM Series Compensation Z vs. QTg - NISM Analysis

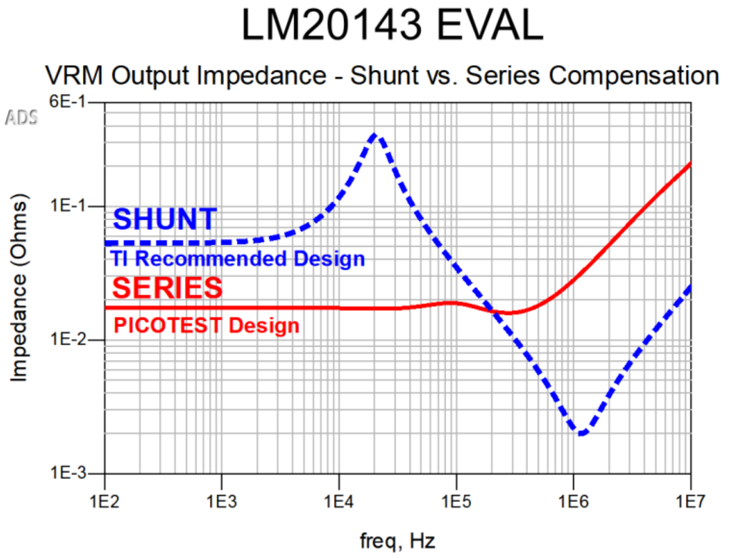
**Sandler_NISM_PM: >71 degrees**
**Z Frequency: 60398.011 Hz**
**Q Frequency: 60398.011 Hz**
**Effective Q: 0.021**

**Flat Z means 97% reduction of Q**

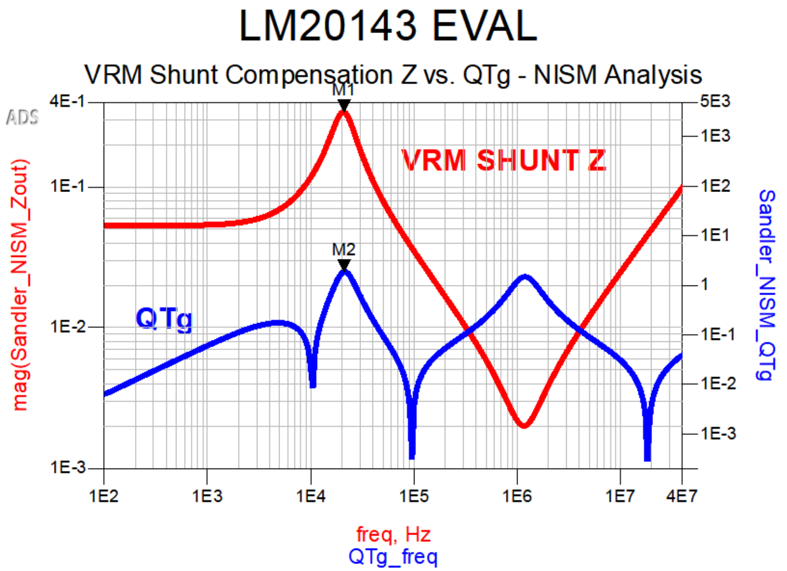
***Non-Invasive Stability Measurement (NISM)**

# CASE 3 - LM20143 Output Impedance & Stability with NISM

## Shunt vs. Series Compensation

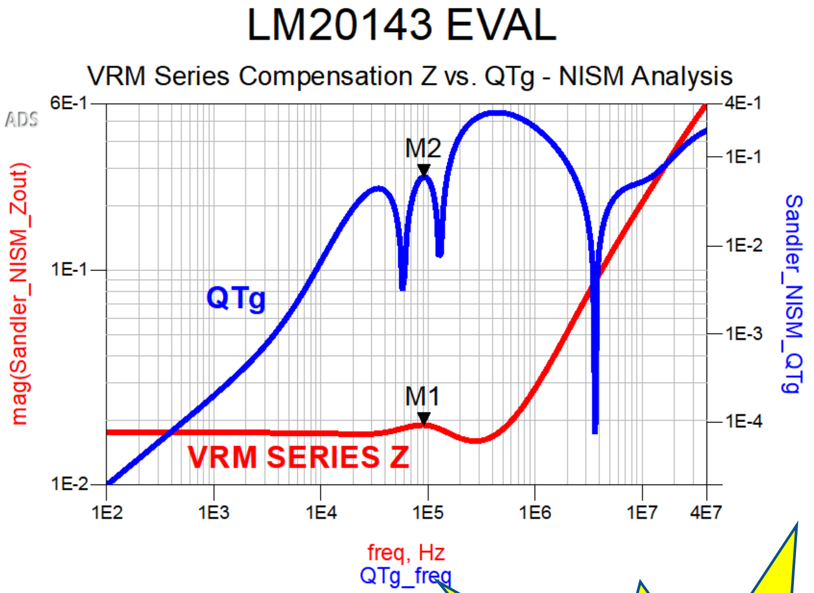

LM20143 EVAL

VRM Output Impedance - Shunt vs. Series Compensation


LM20143 EVAL

VRM Shunt Compensation Z vs. QTg - NISM Analysis

**Sandler_NISM_PM: 27.890 degrees**
**Z Frequency: 20934.058 Hz**
**Q Frequency: 20934.058 Hz**
**Effective Q: 1.869**


LM20143 EVAL

VRM Series Compensation Z vs. QTg - NISM Analysis

**Sandler_NISM_PM: >71 degrees**
**Z Frequency: 91430.028 Hz**
**Q Frequency: 91430.028 Hz**
**Effective Q: 0.060**

**Flat Z means 96.7% reduction of Q**

$$R_{series} = 48.7k\Omega$$

Series compensation allows VRM output Z to be flat -> Better Transient Response

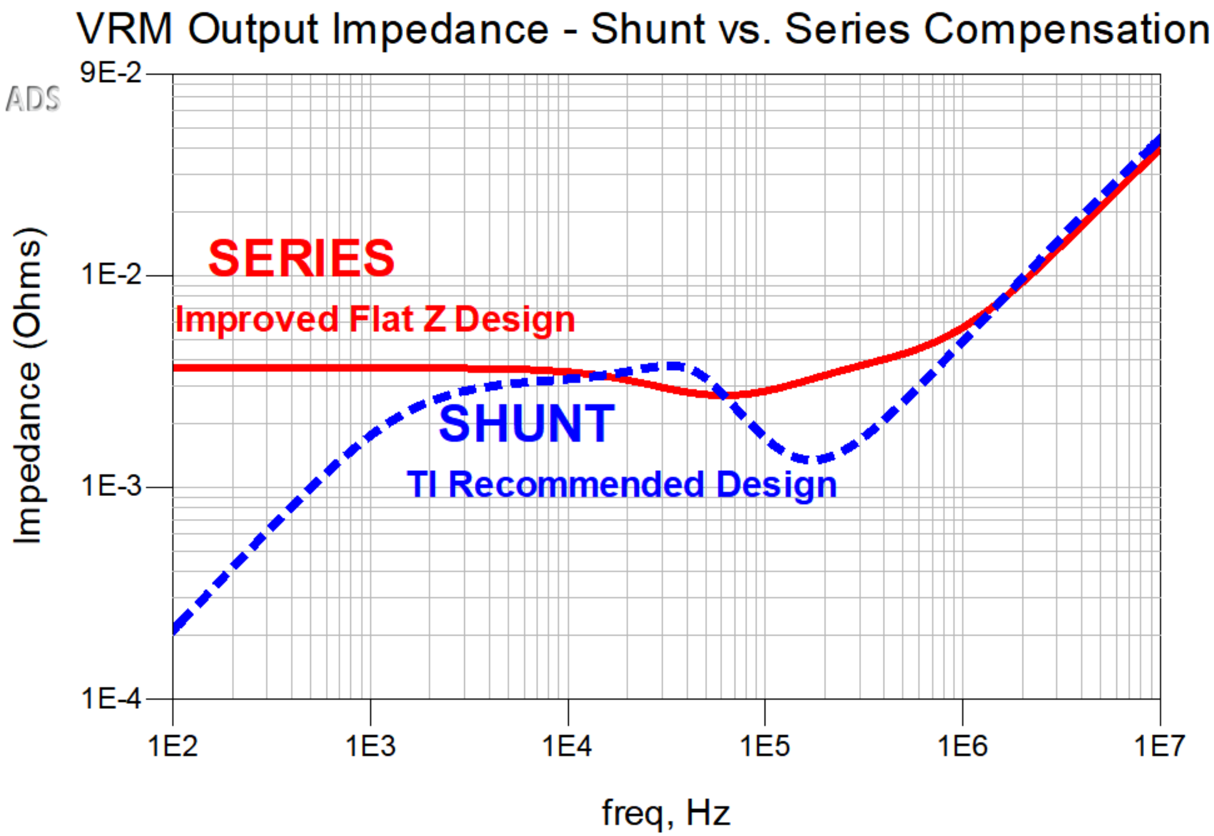
***Non-Invasive Stability Measurement (NISM)**

# CASE 4 – TPS7H4003 Output Impedance

## Shunt vs. Series Compensation

$R_{series} = 70k\Omega$

TPS7H4003 EVAL

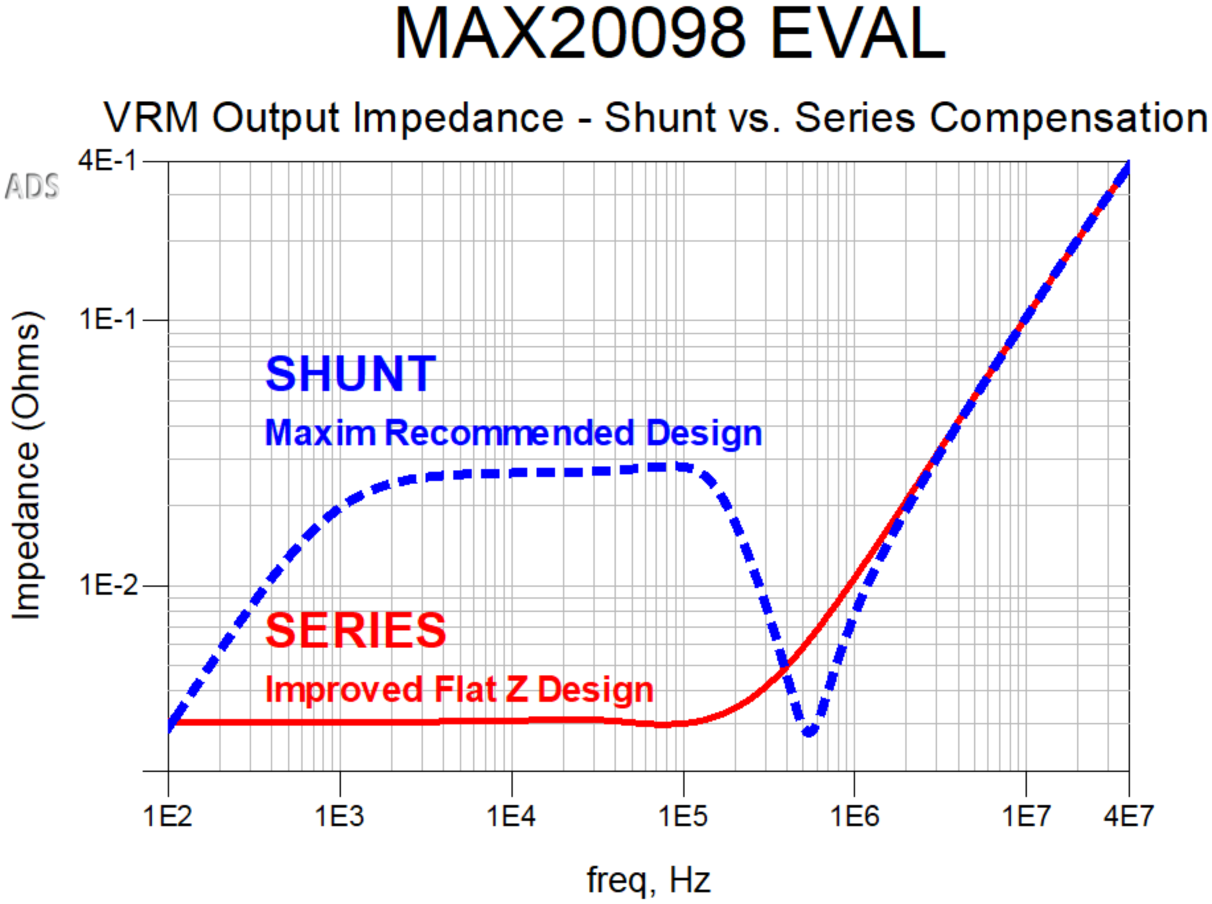


Series compensation allows VRM output Z to be flat -> Better Transient Response

# CASE 5 - MAX20098 Output Impedance & Stability with NISM

## Shunt vs. Series Compensation

$R_{series} = 650\ k\Omega$



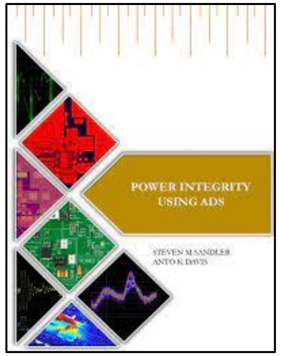
Series compensation allows VRM output Z to be flat -> Better Transient Response

# Call to Action

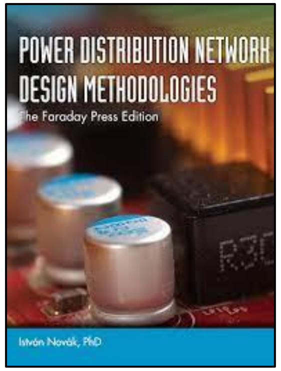
- VRM manufacturers need to provide designers the flexibility to choose between a shunt or series compensation
- Select Current Mode VRMs with the following:
  - Access to Vcomp
  - No internal compensation or at least the ability to disable the internal compensation
- Perfect regulation is a terrible thing……
  - Because that means zero ohms.
- ***Flat VRM output impedance means better dynamic current response!***

# Summary and Conclusions

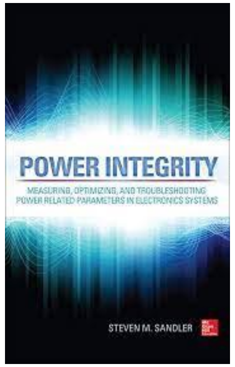
- Series Compensation with a VRM design allows:
  - Better stability
  - Better transient response
  - Flatter VRM design
  - Reduced gain sensitivity
  - Ability to design the VRM to match the impedance of the load
- ***Flatter VRM output impedance means better power delivery to your PDN***



"Power Integrity Using ADS" by S. Sandler



"Power Distribution Network Design Methodologies" by I. Novak



"Power Integrity Measuring, Optimizing, and Troubleshooting Power Related Parameters in Electronics Systems" by S. Sandler

EDI CON ONLINE

# Thank You for Attending

Feel Free to connect with us on LinkedIn

Join the Power Integrity for Distributed Systems LinkedIn Group

Signal Edge Solutions
signal integrity at the edge

PICOTEST

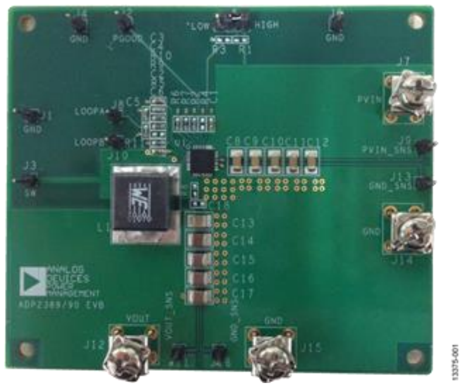
KEYSIGHT
TECHNOLOGIES

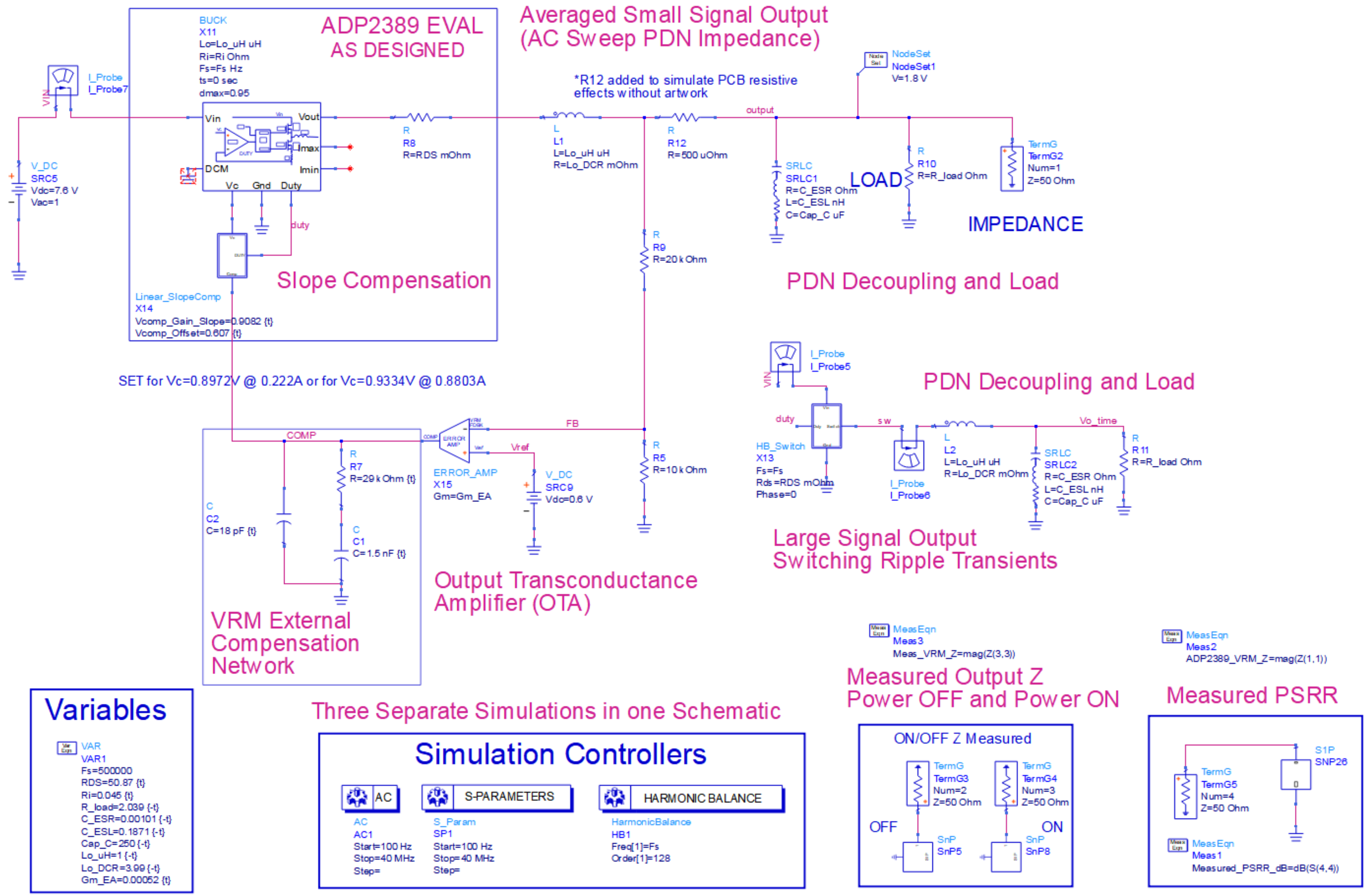
# References

1. Sandler, S. (2018). Characterizing and Selecting the VRM. *Signal Integrity Journal*.
2. Sandler, S. M., & Davis, A. K. (2019). *Power Integrity Using Ads*. Faraday Press.
3. Picotest NISM page - https://www.picotest.com/measurements/NISM.html
4. Erickson, R. W., & Maksimović Dragan. (2012). *Fundamentals of Power Electronics*. Springer Science + Business Media.
5. Franco, S. (2006). *Design with operational amplifiers and Analog Integrated Circuits*. McGraw-Hill.
6. Maniktala, S. (2012). *Switching power supplies A-Z, 2E*. Elsevier Science & Technology.
7. Novak, I. (2021). *Power Distribution Network Design Methodologies*. Faraday Press.
8. S. Sandler, “How to Design for Power Integrity” Keysight sponsored YouTube Video Series: http://www.keysight.com/find/how-to-videos-for-pi
9. Keysight PathWave ADS Site - https://www.keysight.com/us/en/products/software/pathwave-design-software/pathwave-advanced-design-system.html
10. Qiao, M., Parto, P., & Amirani, R. (2002, November 14). *Stabilizing Buck Converters with transconductance amplifiers*. EETimes. Retrieved September 4, 2022, from https://www.eetimes.com/stabilizing-buck-converters-with-transconductance-amplifiers/
11. Sandler, S. M. (2014). *Power integrity: Measuring, optimizing, and troubleshooting power related parameters in Electronics Systems*. McGraw Hill Education.

# CASE 1 - ADP2389 EVAL - ADI Design

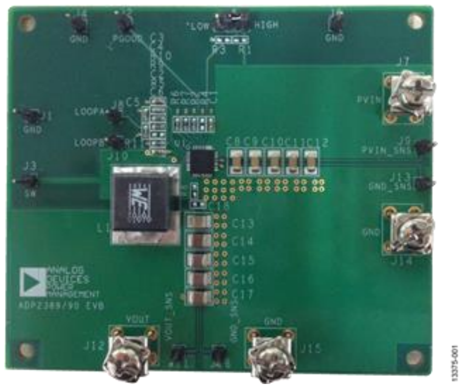
## Shunt Compensation

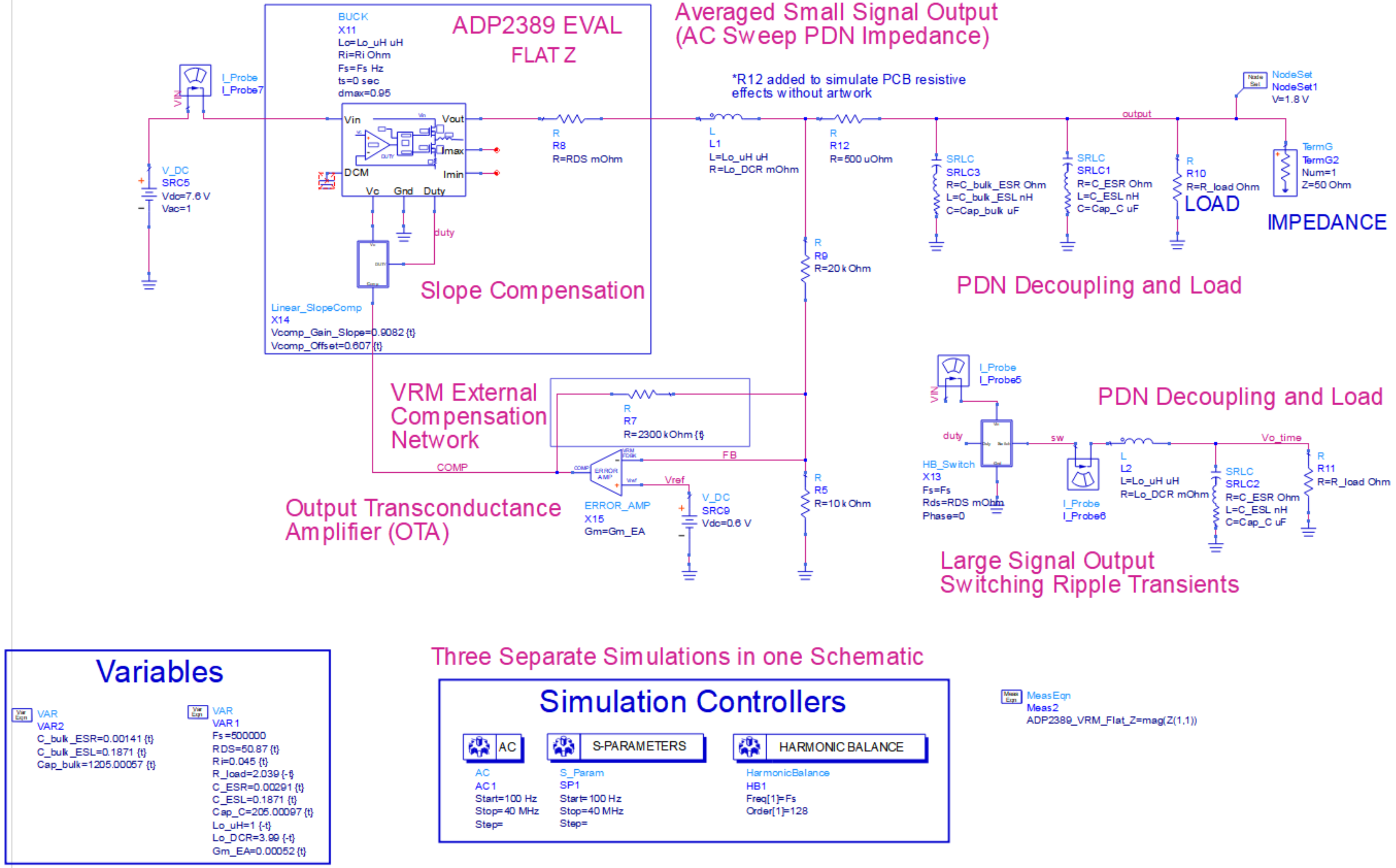




# CASE 1 - ADP2389 EVAL - Flat Z Design

## Series Compensation





### Variables

VAR
VAR2
C_bulk_ESR=0.00141 {t}
C_bulk_ESL=0.1871 {t}
Cap_bulk=1205.00057 {t}

VAR
VAR1
Fs=500000
RDS=50.87 {t}
Ri=0.045 {t}
R_load=2.039 {-t}
C_ESR=0.00291 {t}
C_ESL=0.1871 {t}
Cap_C=205.00097 {t}
Lo_uH=1 {-t}
Lo_DCR=3.99 {-t}
Gm_EA=0.00052 {t}

### Simulation Controllers

AC
AC1
Start=100 Hz
Stop=40 MHz
Step=

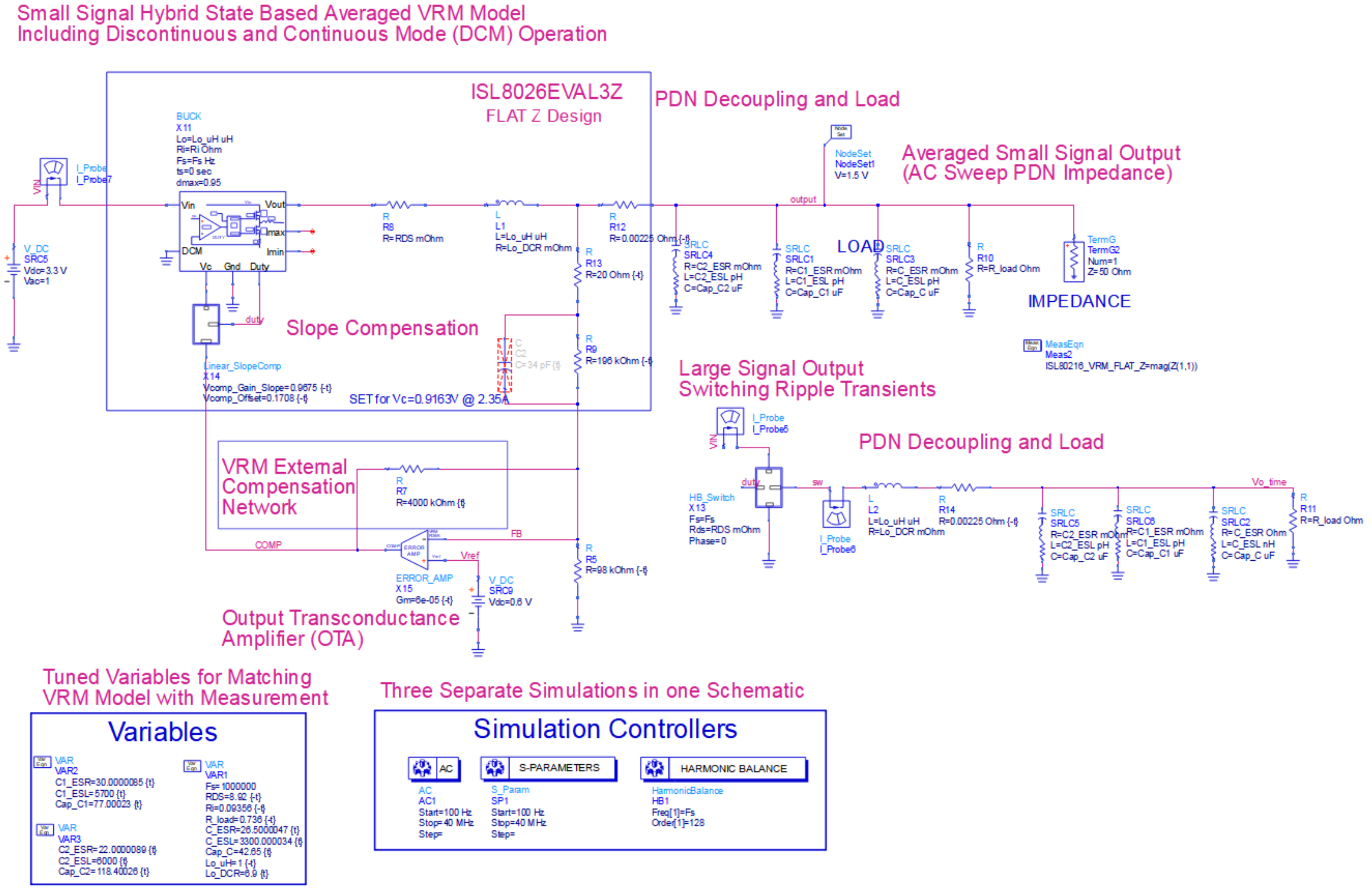
S_Param
SP1
Start=100 Hz
Stop=40 MHz
Step=

HarmonicBalance
HB1
Freq[1]=Fs
Order[1]=128

MeasEqn
Meas2
ADP2389_VRM_Flat_Z=mag(Z(1,1))

# CASE 2 - ISL8026 EVAL – Flat Z Design

## Series Compensation


Small Signal Hybrid State Based Averaged VRM Model
Including Discontinuous and Continuous Mode (DCM) Operation

ISL8026EVAL3Z
FLAT Z Design

PDN Decoupling and Load

Averaged Small Signal Output
(AC Sweep PDN Impedance)

Slope Compensation

SET for Vc=0.9163V @ 2.35A

Large Signal Output
Switching Ripple Transients

PDN Decoupling and Load

VRM External Compensation Network

Output Transconductance Amplifier (OTA)

Tuned Variables for Matching
VRM Model with Measurement

Variables

VAR
VAR2
C1_ESR=30.0000085 {t}
C1_ESL=5700 {t}
Cap_C1=77.00023 {t}

VAR
VAR3
C2_ESR=22.0000089 {t}
C2_ESL=6000 {t}
Cap_C2=118.40026 {t}

VAR
VAR1
Fs=1000000
RDS=8.92 {-t}
Ri=0.09356 {-t}
R_load=0.736 {-t}
C_ESR=26.5000047 {t}
C_ESL=3300.000034 {t}
Cap_C=42.65 {t}
Lo_uH=1 {-t}
Lo_DCR=6.9 {t}

Three Separate Simulations in one Schematic

Simulation Controllers

AC
AC1
Start=100 Hz
Stop=40 MHz
Step=

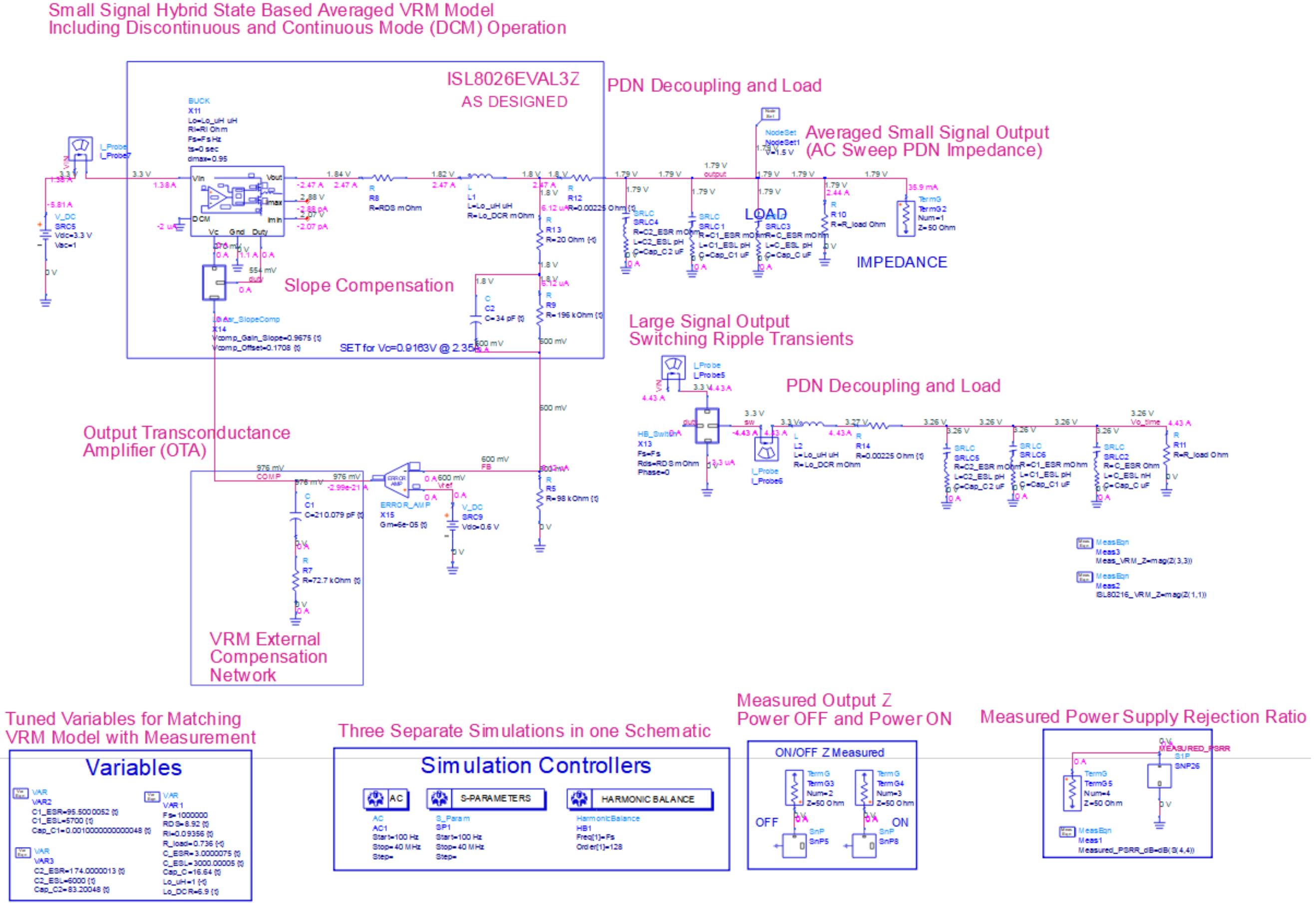
S_Param
SP1
Start=100 Hz
Stop=40 MHz
Step=

HarmonicBalance
HB1
Freq[1]=Fs
Order[1]=128

MeasEqn
Meas2
ISL80216_VRM_FLAT_Z=mag(Z(1,1))

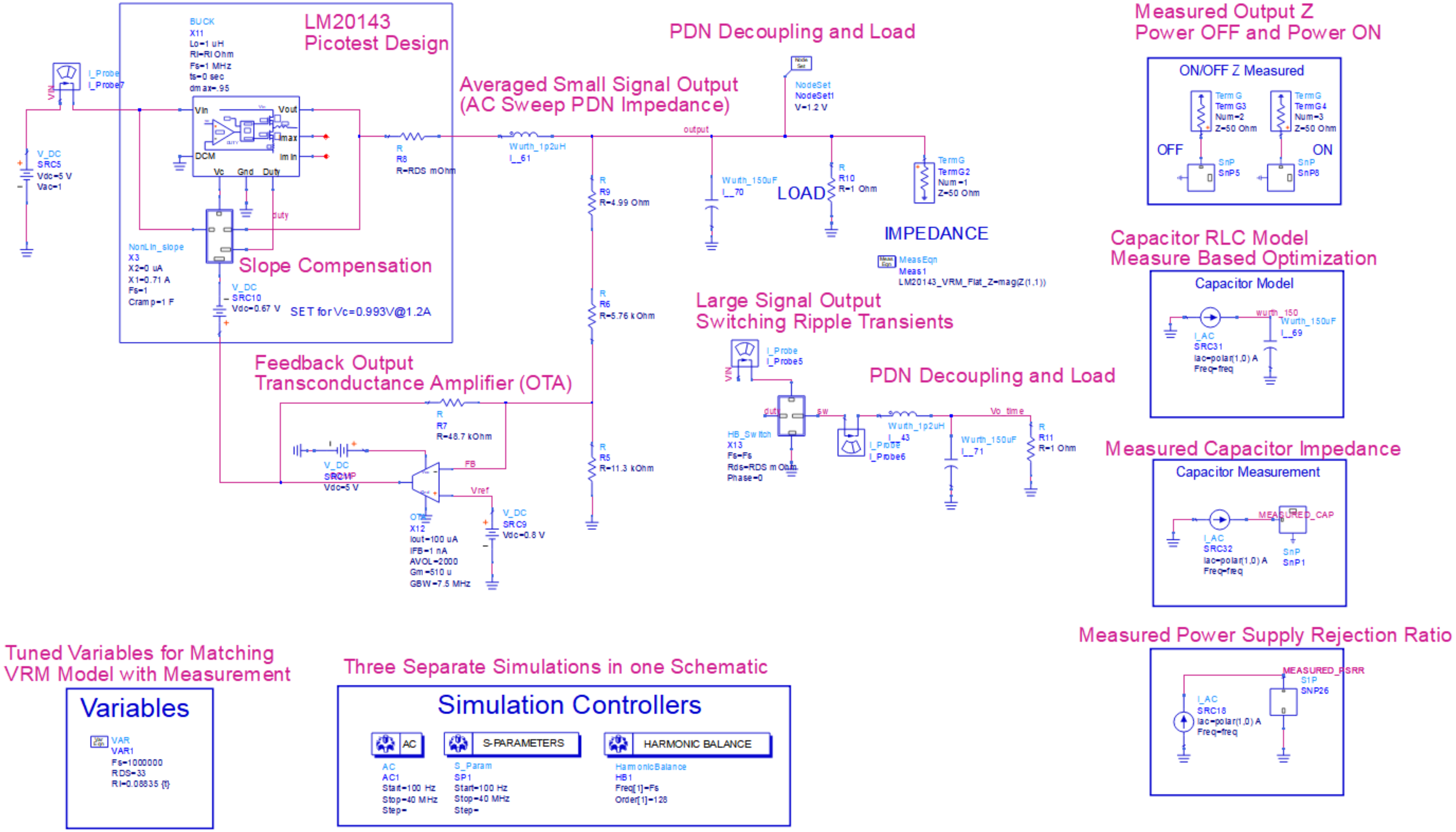
# CASE 2 - ISL8026 EVAL – Intersil Design

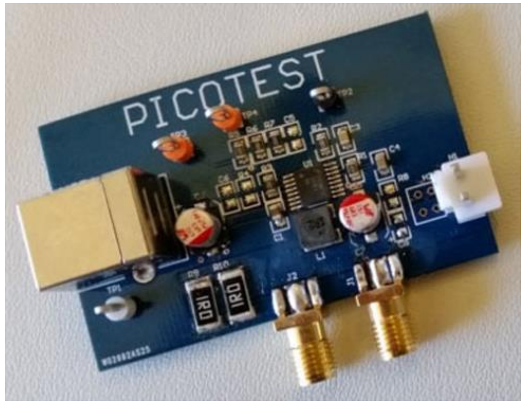
## Shunt Compensation



# CASE 3 - LM20143 – Picotest Design

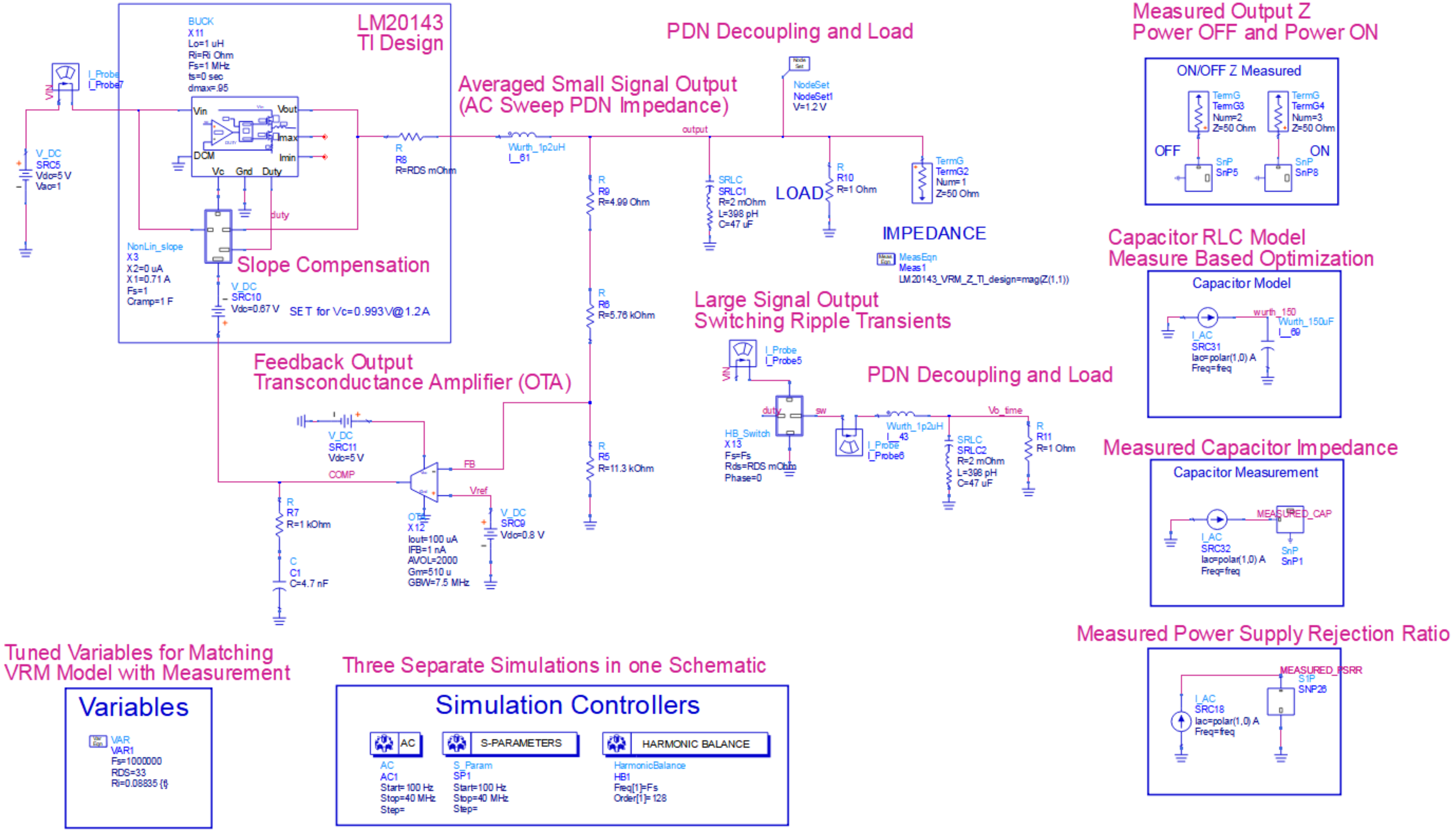
## Series Compensation

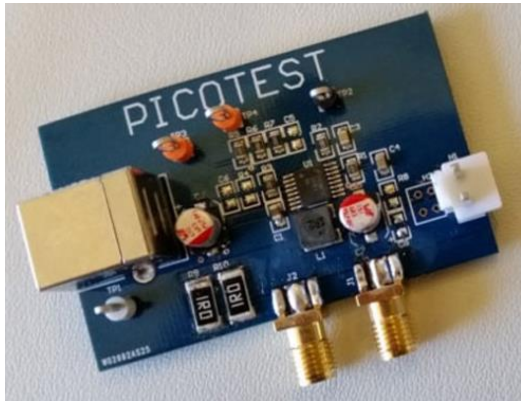




# CASE 3 - LM20143 – TI Design

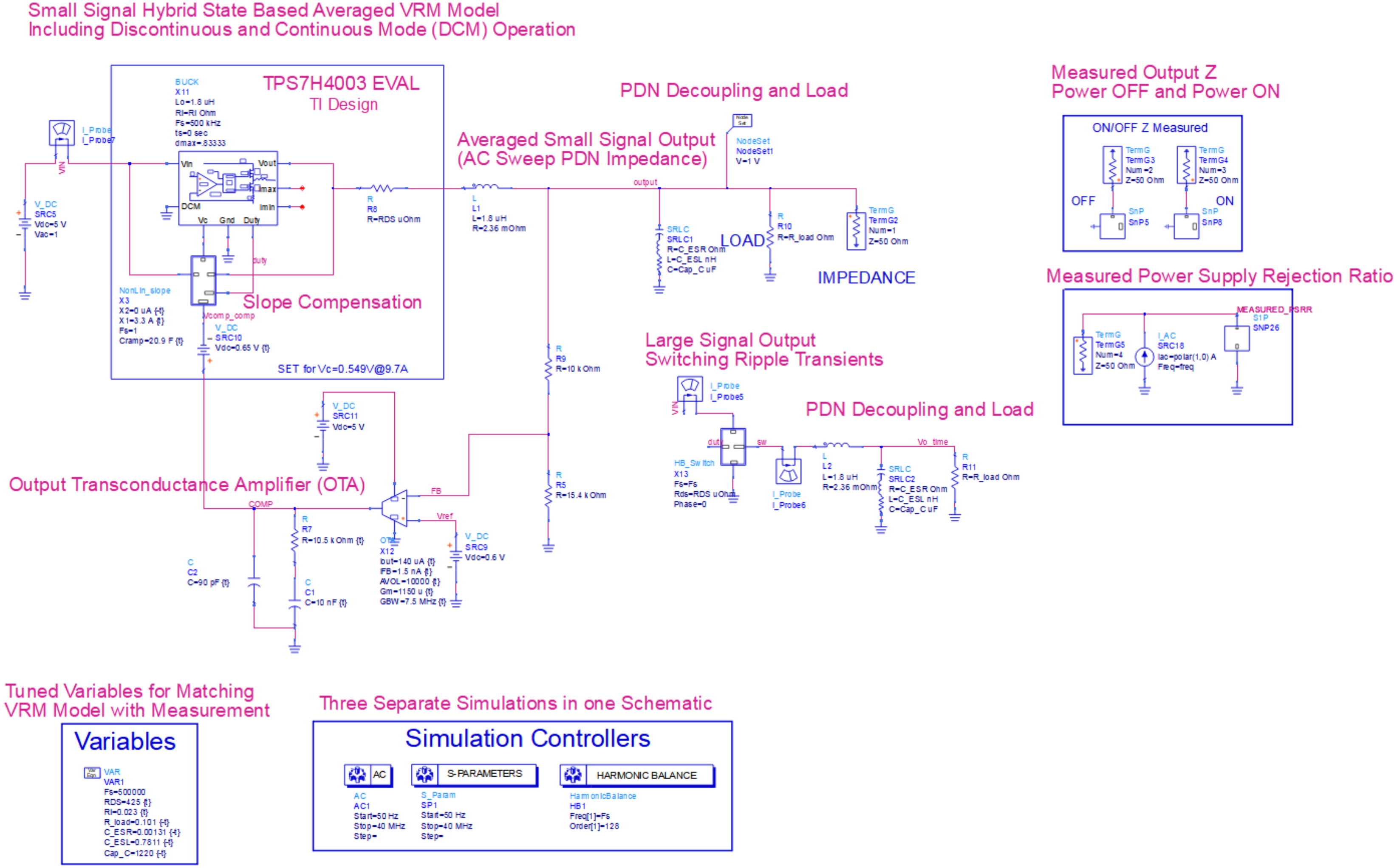
## Shunt Compensation





# CASE 4 - TPS7H4003 EVAL – TI Design

## Shunt Compensation


Small Signal Hybrid State Based Averaged VRM Model Including Discontinuous and Continuous Mode (DCM) Operation

TPS7H4003 EVAL
TI Design

Slope Compensation

SET for Vc=0.549V@9.7A

Output Transconductance Amplifier (OTA)

Averaged Small Signal Output (AC Sweep PDN Impedance)

PDN Decoupling and Load

Large Signal Output Switching Ripple Transients

PDN Decoupling and Load

Measured Output Z Power OFF and Power ON

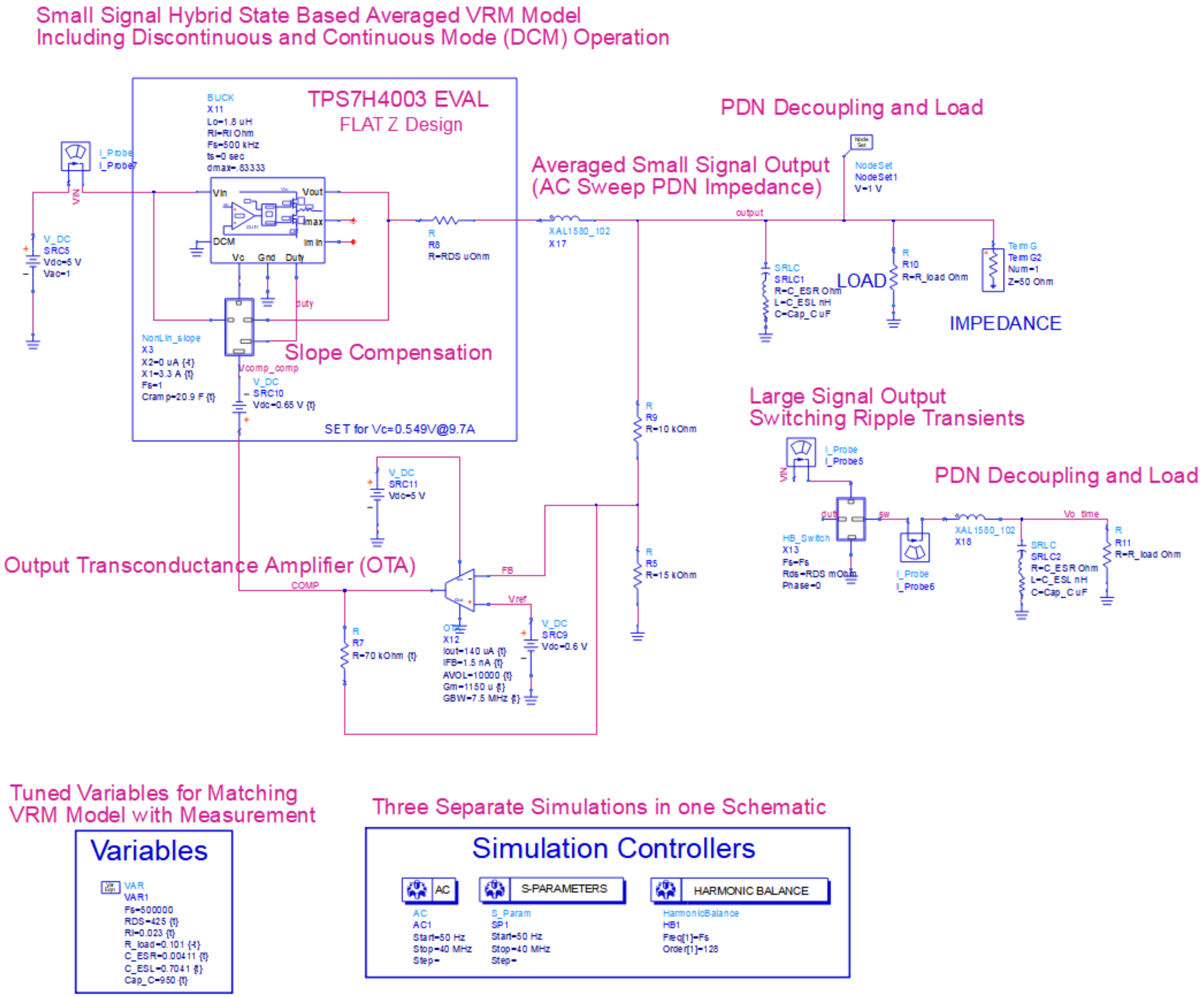
Measured Power Supply Rejection Ratio

Tuned Variables for Matching VRM Model with Measurement

Three Separate Simulations in one Schematic

# CASE 4 - TPS7H4003 EVAL – Flat Z Design

## Series Compensation


Small Signal Hybrid State Based Averaged VRM Model
Including Discontinuous and Continuous Mode (DCM) Operation

TPS7H4003 EVAL
FLAT Z Design

BUCK
X11
Lo=1.8 uH
Rl=Rl Ohm
Fs=500 kHz
ts=0 sec
dmax=.83333

V_DC
SRC5
Vdc=5 V
Vac=1

NonLin_slope
X3
X2=0 uA {-t}
X1=3.3 A {t}
Fs=1
Cramp=20.9 F {t}

Slope Compensation

V_DC
SRC10
Vdc=0.65 V {t}

SET for Vc=0.549V@9.7A

R
R8
R=RDS uOhm

Averaged Small Signal Output
(AC Sweep PDN Impedance)

PDN Decoupling and Load

NodeSet
NodeSet1
V=1 V

SRLC
SRLC1
R=C_ESR Ohm
L=C_ESL nH
C=Cap_C uF

R
R10
R=R_load Ohm

Term G
Term G2
Num=1
Z=50 Ohm

R
R9
R=10 kOhm

R
R5
R=15 kOhm

V_DC
SRC11
Vdc=5 V

Output Transconductance Amplifier (OTA)

R
R7
R=70 kOhm {t}

OTA
X12
Iout=140 uA {t}
IFB=1.5 nA {t}
AVOL=10000 {t}
Gm=1150 u {t}
GBW=7.5 MHz {t}

V_DC
SRC9
Vdc=0.6 V

Large Signal Output
Switching Ripple Transients

PDN Decoupling and Load

HB_Switch
X13
Fs=Fs
Rds=RDS mOhm
Phase=0

SRLC
SRLC2
R=C_ESR Ohm
L=C_ESL nH
C=Cap_C uF

R
R11
R=R_load Ohm

Tuned Variables for Matching
VRM Model with Measurement

Variables

VAR
VAR1
Fs=500000
RDS=425 {t}
Rl=0.023 {t}
R_load=0.101 {-t}
C_ESR=0.00411 {t}
C_ESL=0.7041 {t}
Cap_C=950 {t}

Three Separate Simulations in one Schematic

Simulation Controllers

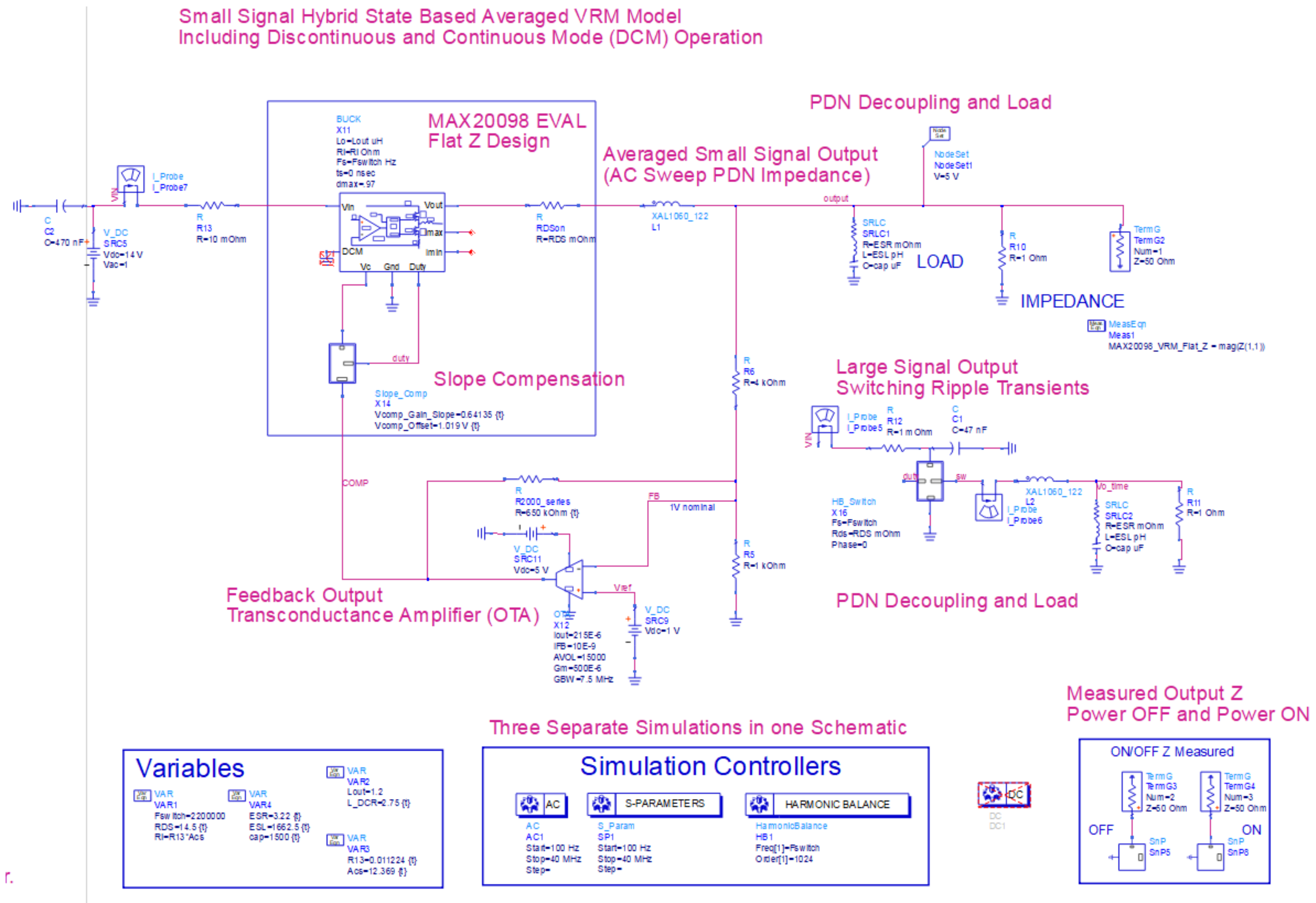
AC
AC1
Start=50 Hz
Stop=40 MHz
Step=

S_Param
SP1
Start=50 Hz
Stop=40 MHz
Step=

HarmonicBalance
HB1
Freq[1]=Fs
Order[1]=128

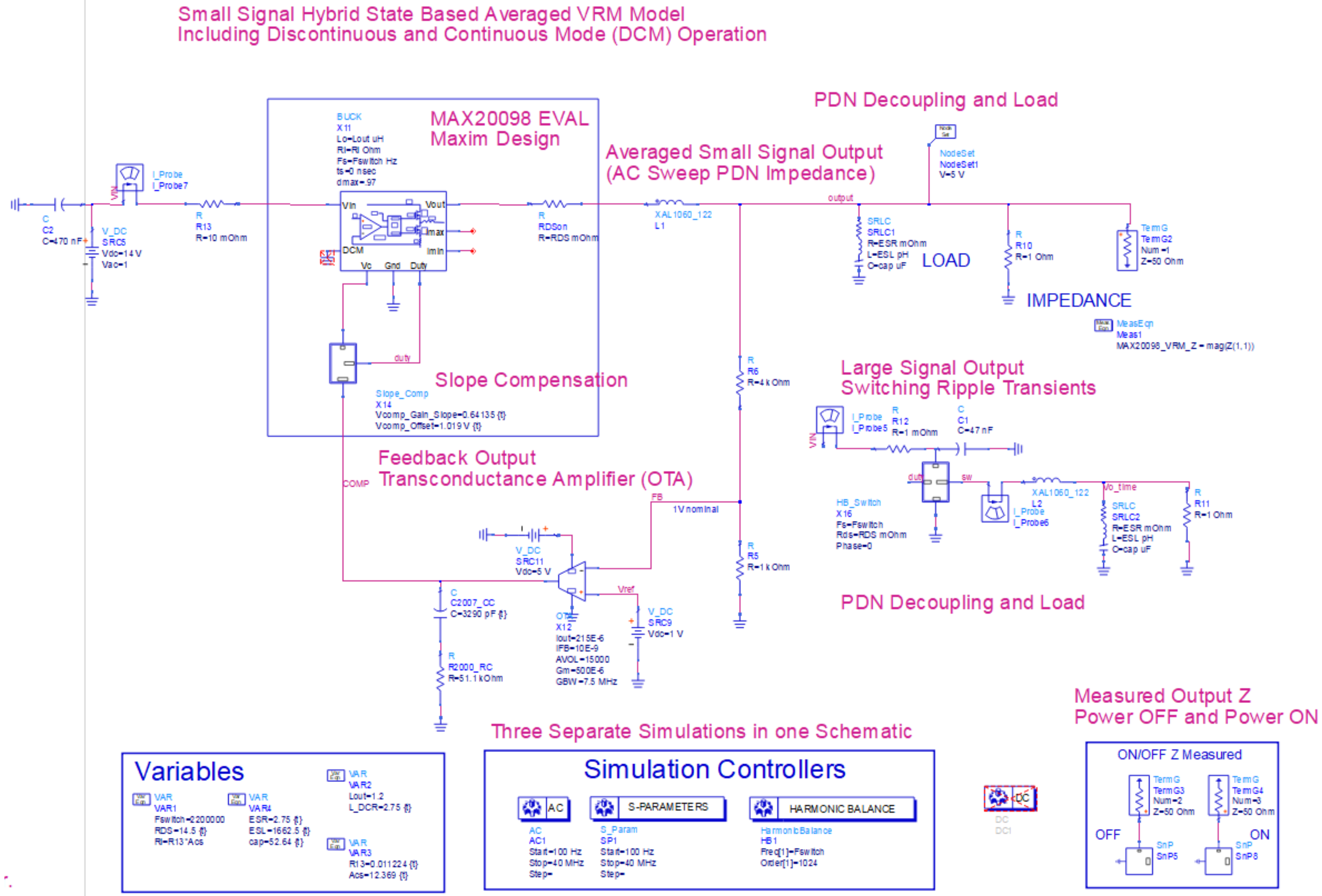
# CASE 5 - MAX20098 – Flat Z Design

## Series Compensation



# CASE 5 - MAX20098 – MAXIM Design

## Shunt Compensation



# END OF SLIDES

Signal Edge Solutions
signal integrity at the edge

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